

Strong thermal leptogenesis in the $SO(10)$ -inspired model

*a complete picture of the low energy neutrino
parameters*

by: Luca Marzola



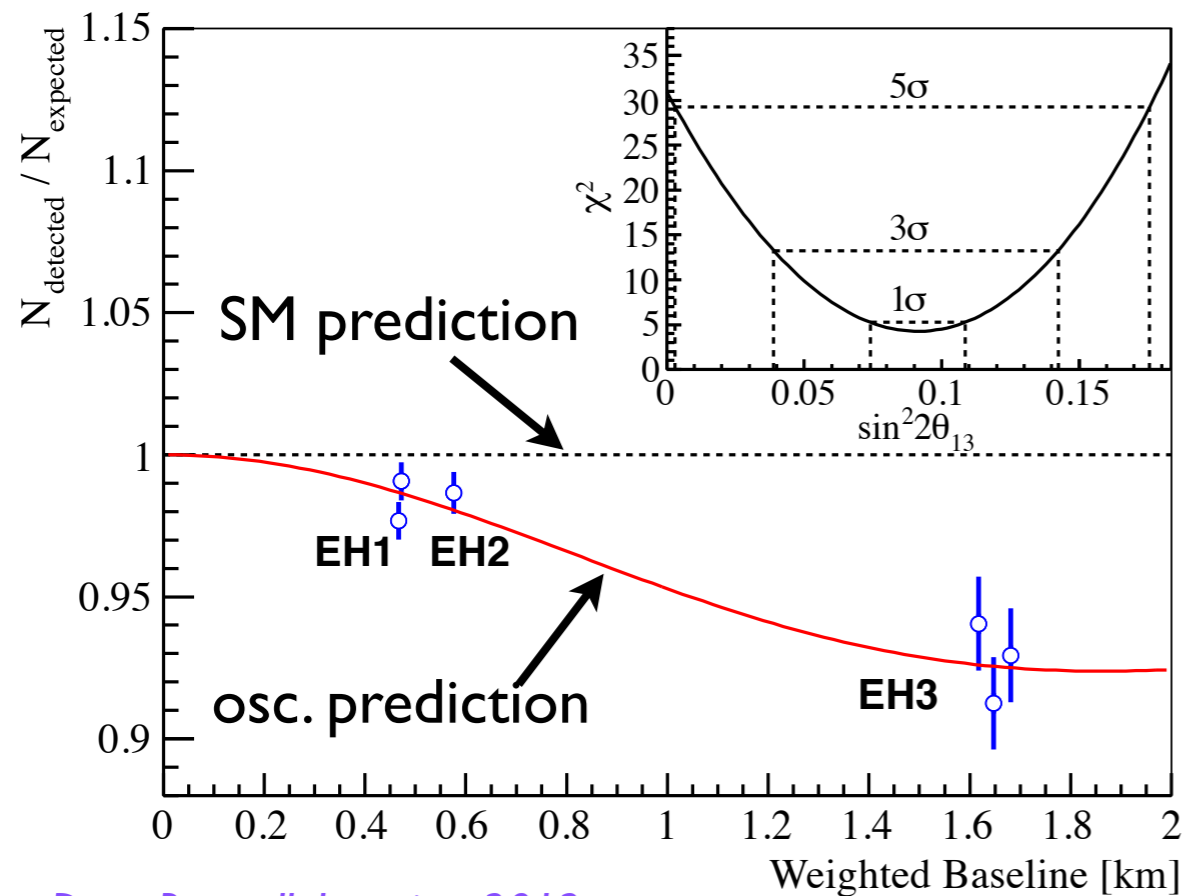
Based on:

- P. Di Bari, LM: *SO(10)-inspired solution to the problem of the initial conditions in leptogenesis* - Nucl.Phys. B877 (2013)
- P. Di Bari, S.Blanchet, D.A. Jones, LM: *Leptogenesis with heavy neutrino flavours: from density matrix to Boltzmann equations* - JCAP 1301 (2013)
- P. Di Bari, E. Bertuzzo, LM: *The problem of the initial conditions in flavoured leptogenesis and the τN_2 -dominated scenario* - Nucl.Phys. B849 (2011)

Two Problems...

The current paradigms of Particle Physics (Standard Model) and Cosmology (Λ -CDM Model) do not explain:

- Neutrino oscillations
- Baryon asymmetry of the Universe



Daya Bay collaboration, 2012



... one solution: Leptogenesis

- Minimal type I Seesaw extension of the Standard Model:

$$\mathcal{L} = \mathcal{L}_{SM} + i\overline{N_{Ri}}\partial^\mu\gamma_\mu N_{Ri} - h_{\alpha i}\overline{\ell_{L\alpha}}N_{Ri}\tilde{\Phi} - \frac{1}{2}\overline{N_{Ri}^c}D_{M_i}N_{Rj} + \text{H.c.}$$

$(i = 1, 2, 3) \quad (\alpha = e, \mu, \tau)$

- 3 RH neutrinos with a Majorana mass term
- Yukawa term for neutrinos

$$D_x := \text{diag}(X_1, X_2, X_3)$$

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S.B. + Heavy R.H.N.

$$-(m_D)_{\alpha i}\overline{\nu_{L\alpha}}N_{Ri} \quad [M] \gg [m_D]$$

→ **Type I Seesaw:**

$$M_{light} \approx -m_D M^{-1} m_D^T$$

$$M_{heavy} \approx M$$

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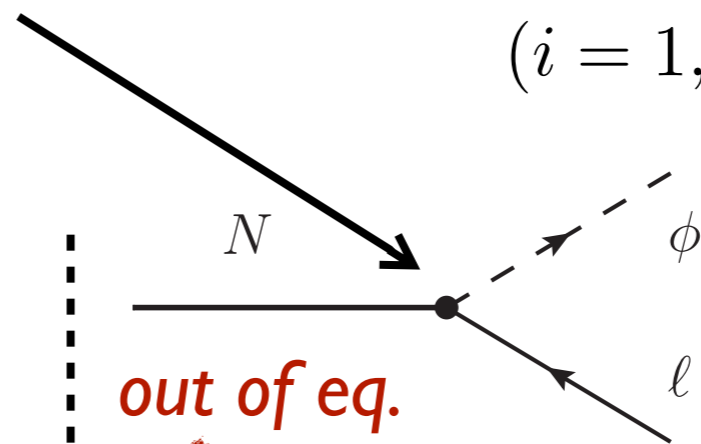
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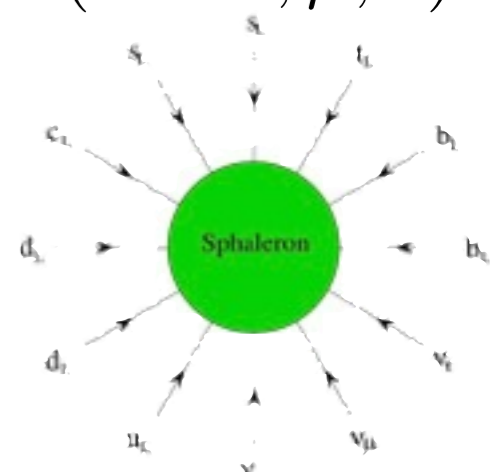
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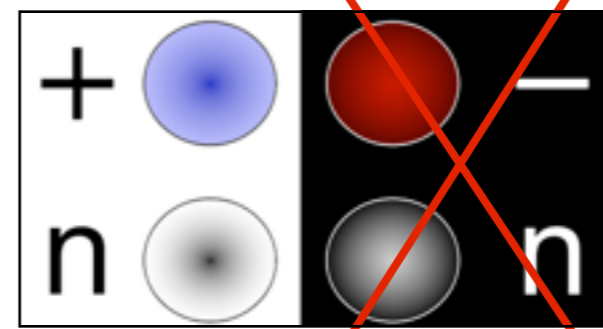
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SM Sphaleron:

$$\Delta B \neq 0 \quad \Delta L \neq 0$$

$$\Delta(B - L) = 0$$



$$\eta_B \simeq 10^{-2} N_{B-L}^f$$

SO(10)-inspired framework

- The model introduces 18 new parameters, can it be predictive?

Shift the parametrization as follows:

$$15 + 3 \rightarrow 6 + 3 + 6 + 3$$

$$h_{\alpha i}, M_i \rightarrow U, m_i, V_L, m_{D_i}$$

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neutrino oscillation experiments
(info on mixing angles in U and mass splittings)

P. Di Bari, A. Riotto, 2008
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($m_{D_i} \sim m_{\nu i}, V_L \sim V_{CKM}$)

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- The resulting heavy neutrino mass spectrum is hierarchical:

$$M_3 > 10^{12} \text{ GeV} > M_2 > 10^9 \text{ GeV} \gg M_1$$

- Leptogenesis is dominated by the dynamics of N_2
- The B-L asymmetry evolves through a sequence of separated stages each described by a set of flavoured Boltzmann equations.

S. Blanchet, P. Di Bari, D.A. Jones, LM, 2013

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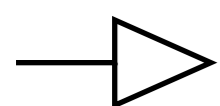
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we can constrain the parameter space of the model by requiring $\eta_B^{lept} \approx \eta_B^0$

But which initial conditions?

- An ‘ethical’ problem: unknown initial conditions

Remarkably, 10^{-9} is a natural value for η_B^{lept} . However, we cannot neglect the impact of a possible preexistent B-L asymmetry ($N_{B-L}^{preex,0} \sim \mathcal{O}(1)$?) as it also would contribute into the measured baryon asymmetry:

$$\eta_B^0 \approx 10^{-2} \left(N_{B-L}^{lept,f} + N_{B-L}^{preex,f} \right) \gg 10^{-9}$$

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how to safely impose $\eta_B^{lept} \approx \eta_B^0$ and constrain the $SO(10)$ -inspired model?

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→ Solution: require *strong thermal Leptogenesis*

$$\eta_B^0 \approx 10^{-2} \left(N_{B-L}^{lept,f} + \cancel{N_{B-L}^{preex,f}} \right) \approx 10^{-9} \longleftrightarrow \text{Strong thermal Leptogenesis}$$

E. Bertuzzo, P. Di Bari, LM, 2011

as a result:

- leptogenesis is independent of its (unknown) initial conditions
- imposing $\eta_B^{lept} \approx \eta_B^0$ indeed constrains the model

A remarkable feature:

- Due to *flavour effects*, strong thermal Leptogenesis requires non trivial conditions on key parameters that regulate the dynamics of the Leptogenesis process.

E. Bertuzzo, P. Di Bari & LM, 2011

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E. Bertuzzo, P. Di Bari & LM, 2011

- It is remarkable that within the $SO(10)$ -inspired model *successful strong thermal Leptogenesis can be achieved!*
- It is even more remarkable that *adopting these strong thermal Leptogenesis solutions results in sharp predictions that the $SO(10)$ -inspired model casts on all the low energy neutrino parameters*

Predictions from:



$SO(10)$ -inspired model

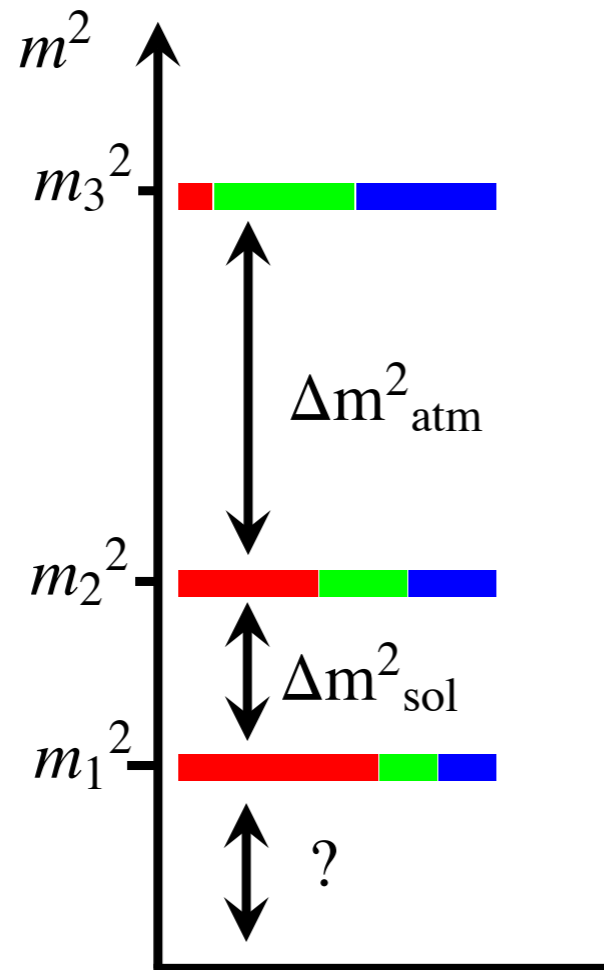
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strong thermal leptogenesis

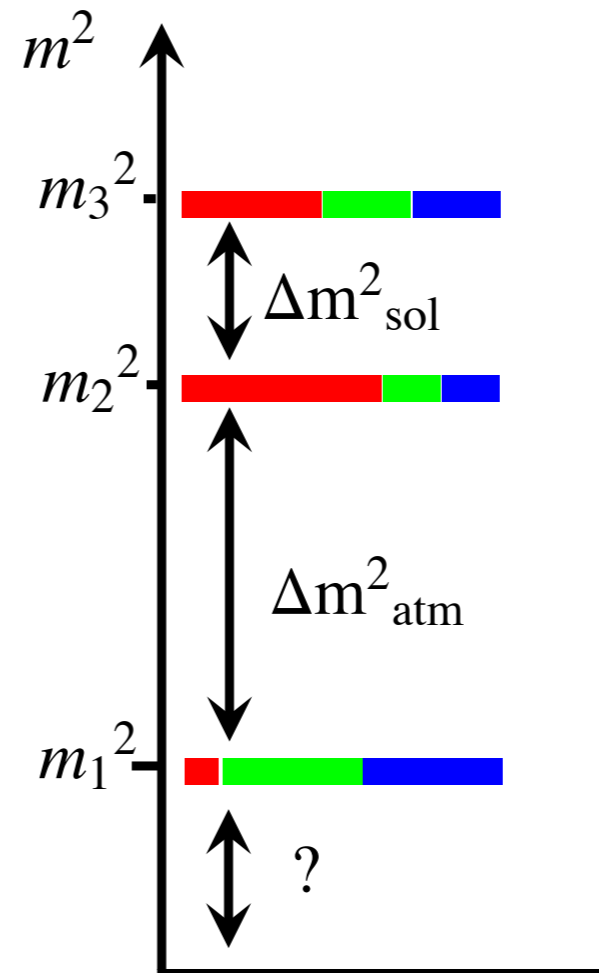
• Light (i.e. ordinary) neutrinos ordering:

■ ν_e ■ ν_μ ■ ν_τ

Normal ordering

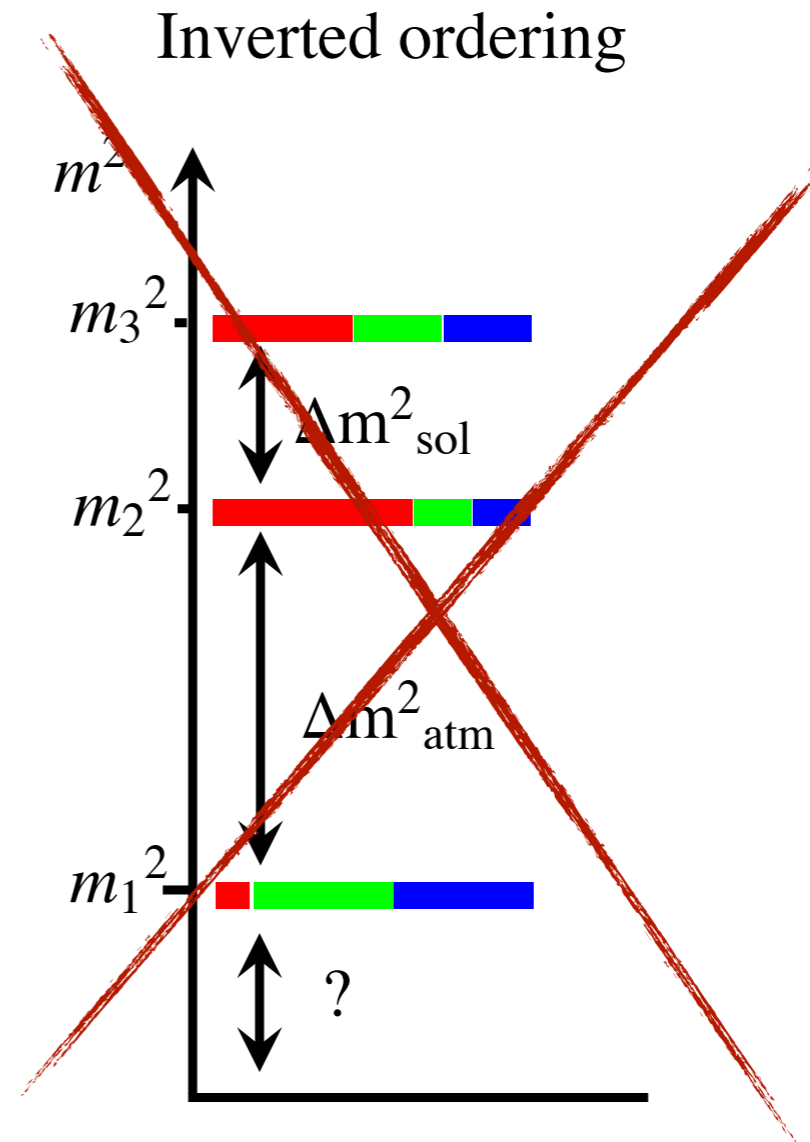
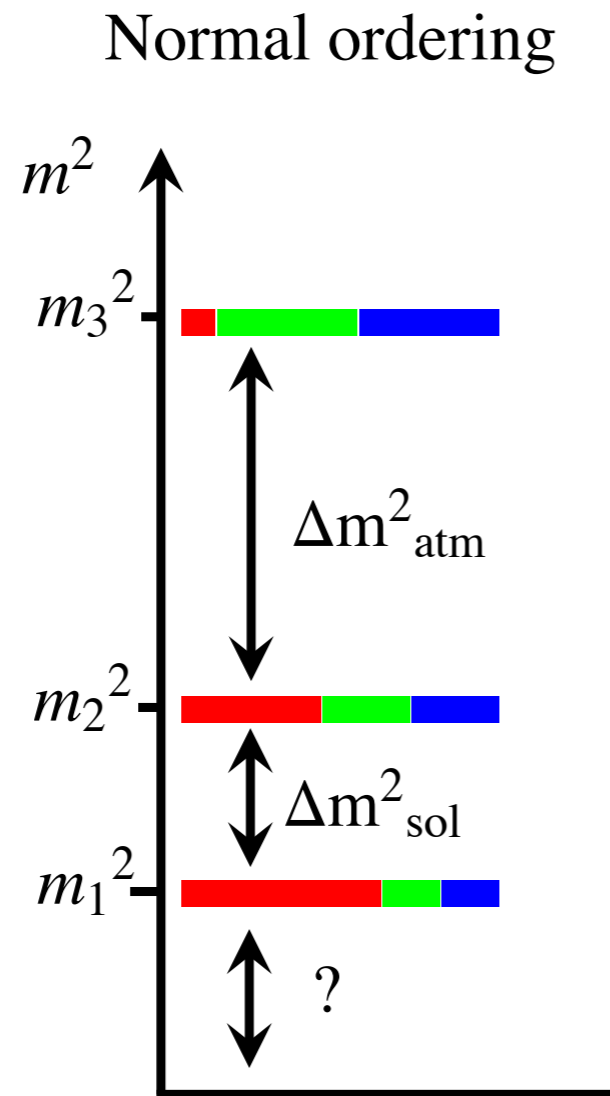


Inverted ordering



• Light (i.e. ordinary) neutrinos ordering:

■ ν_e ■ ν_μ ■ ν_τ



Strong SO(10)-inspired leptogenesis solutions *exclude inverted ordering* as no strong thermal solution is found in this setup

In the following plots:

- yellow regions represent successful Leptogenesis solutions:

$$N_{B-L}^{lept,f} \approx 10^{-7} \longrightarrow \eta_B^{lept} \approx \eta_B^0$$

- other colours quantify the ‘strength’ of the strong thermal solutions:

$$N_{B-L}^{preex,0} = 10^{-3}, 10^{-2}, 10^{-1} \longrightarrow N_{B-L}^{preex,f} < 10^{-8}$$

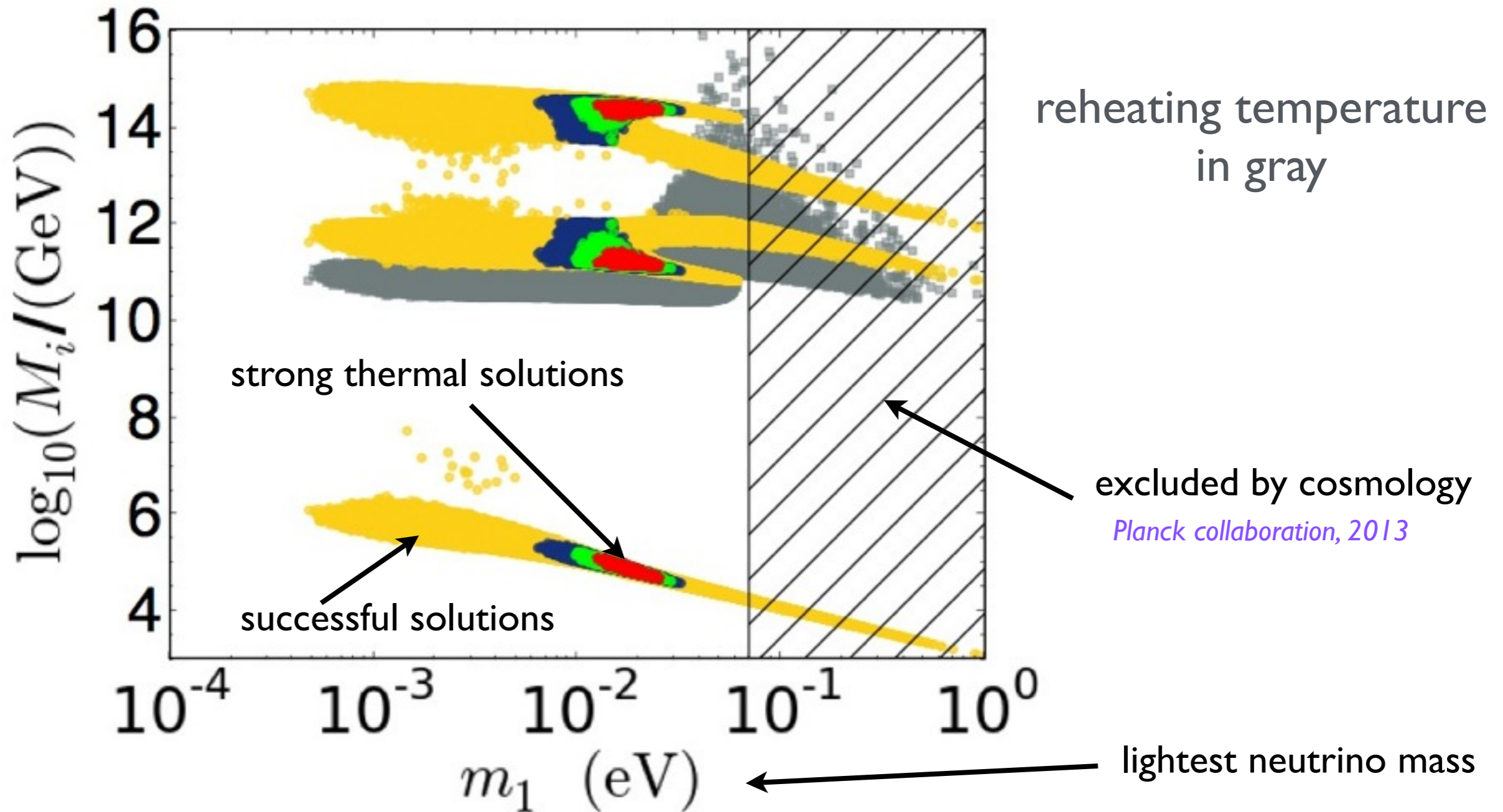
(N.B: strong thermal solutions are also successful solutions)

...and of course everything applies exclusively to normal ordering

● Heavy neutrino mass spectrum:

$$N_{B-L}^{preex,0} = 0, 10^{-3}, 10^{-2}, 10^{-1}$$

$$N_{B-L}^{preex,f} < 10^{-8}$$



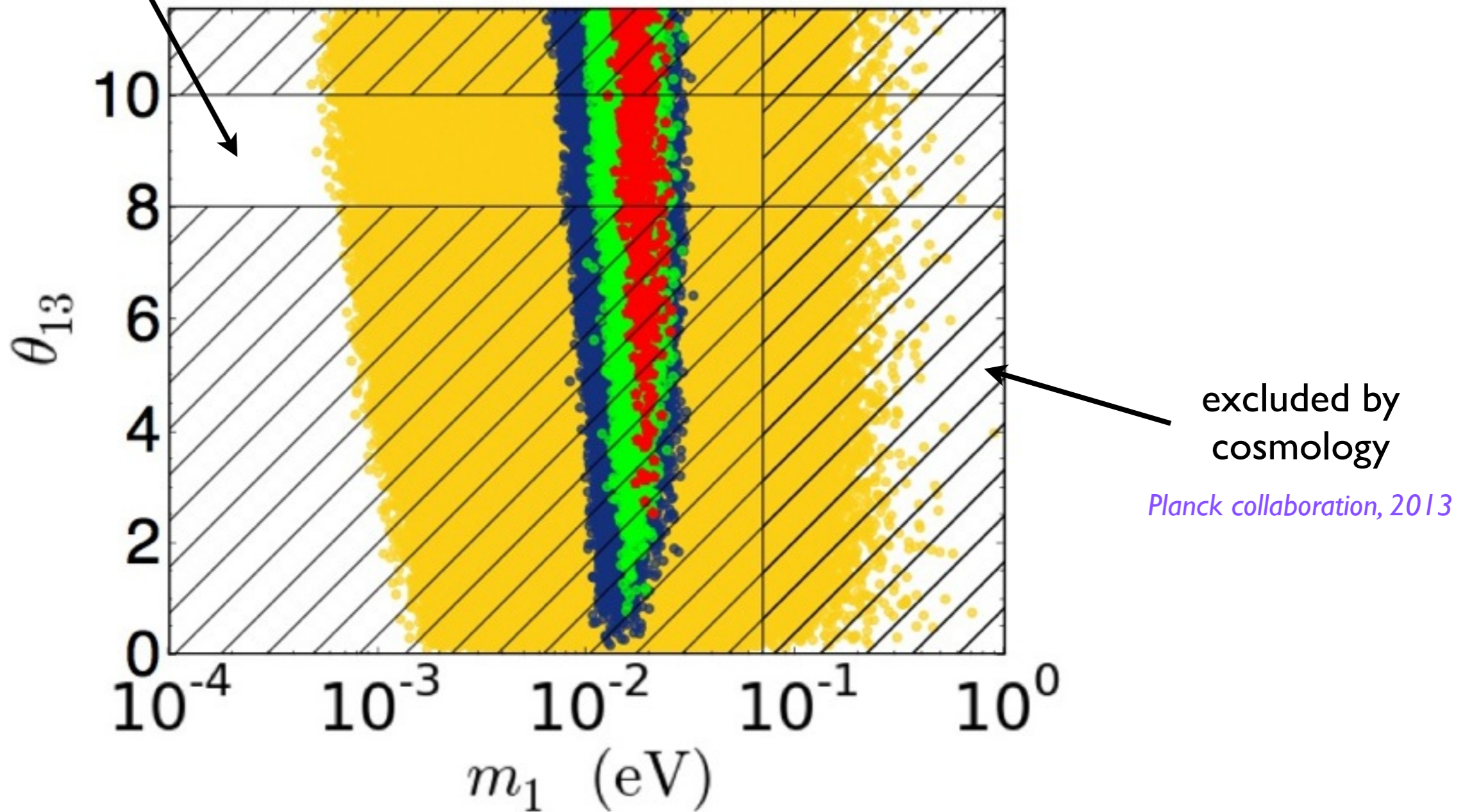
Hierarchical mass spectrum of N_2 -dominated scenarios, as required by the strong thermal leptogenesis conditions

● Reactor mixing angle θ_{13}

$$N_{B-L}^{preex,0} = 0, 10^{-3}, 10^{-2}, 10^{-1}$$

$$N_{B-L}^{preex,f} < 10^{-8}$$

current 2σ range *F. Capozzi et al. 2013*
M.C. Gonzalez-Garcia et al, 2012

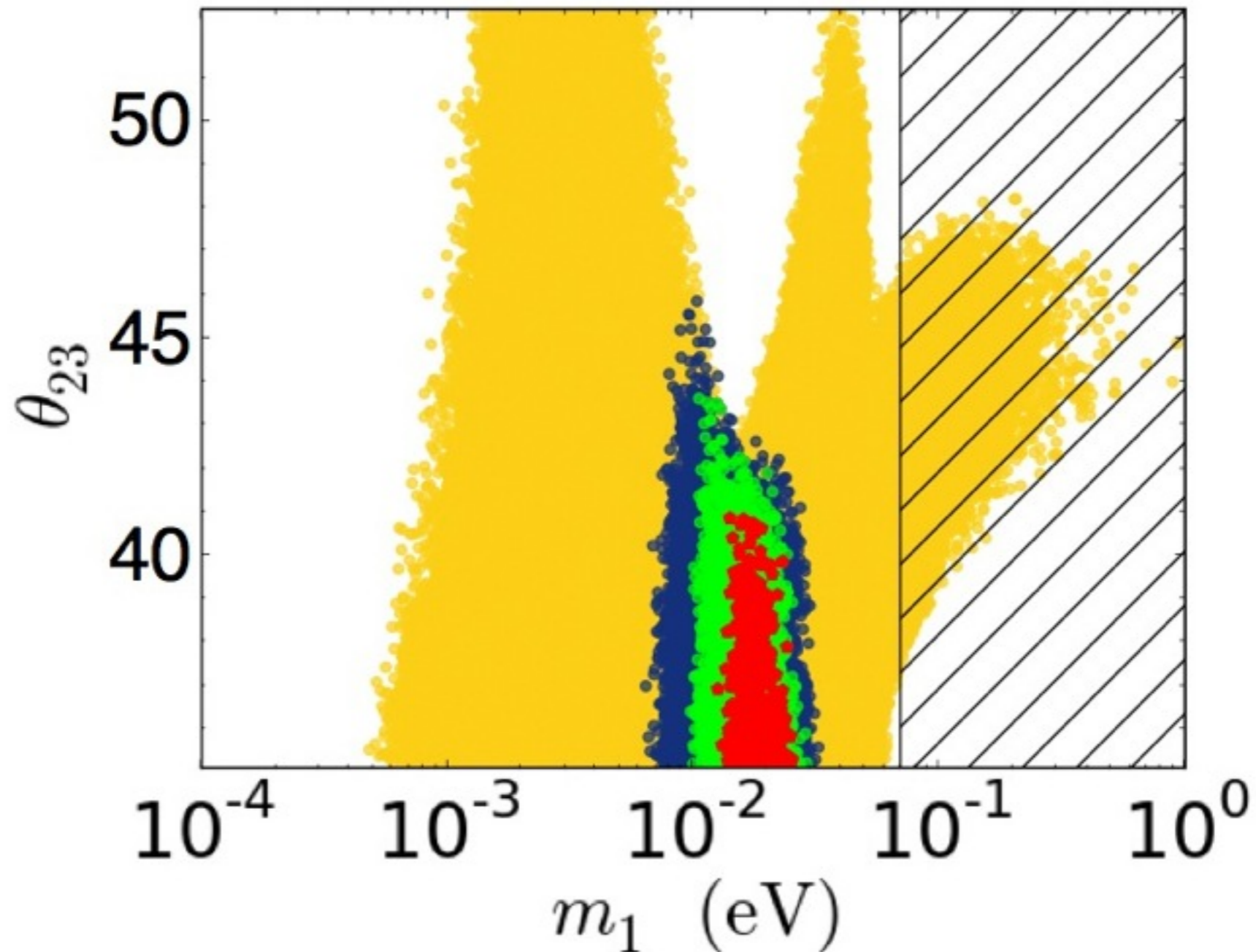


The strong SO(10)-inspired solutions point to *large values of the reactor mixing angle* (lower bound $\theta_{13} > 2^\circ$).

- Atmospheric mixing angle θ_{23}

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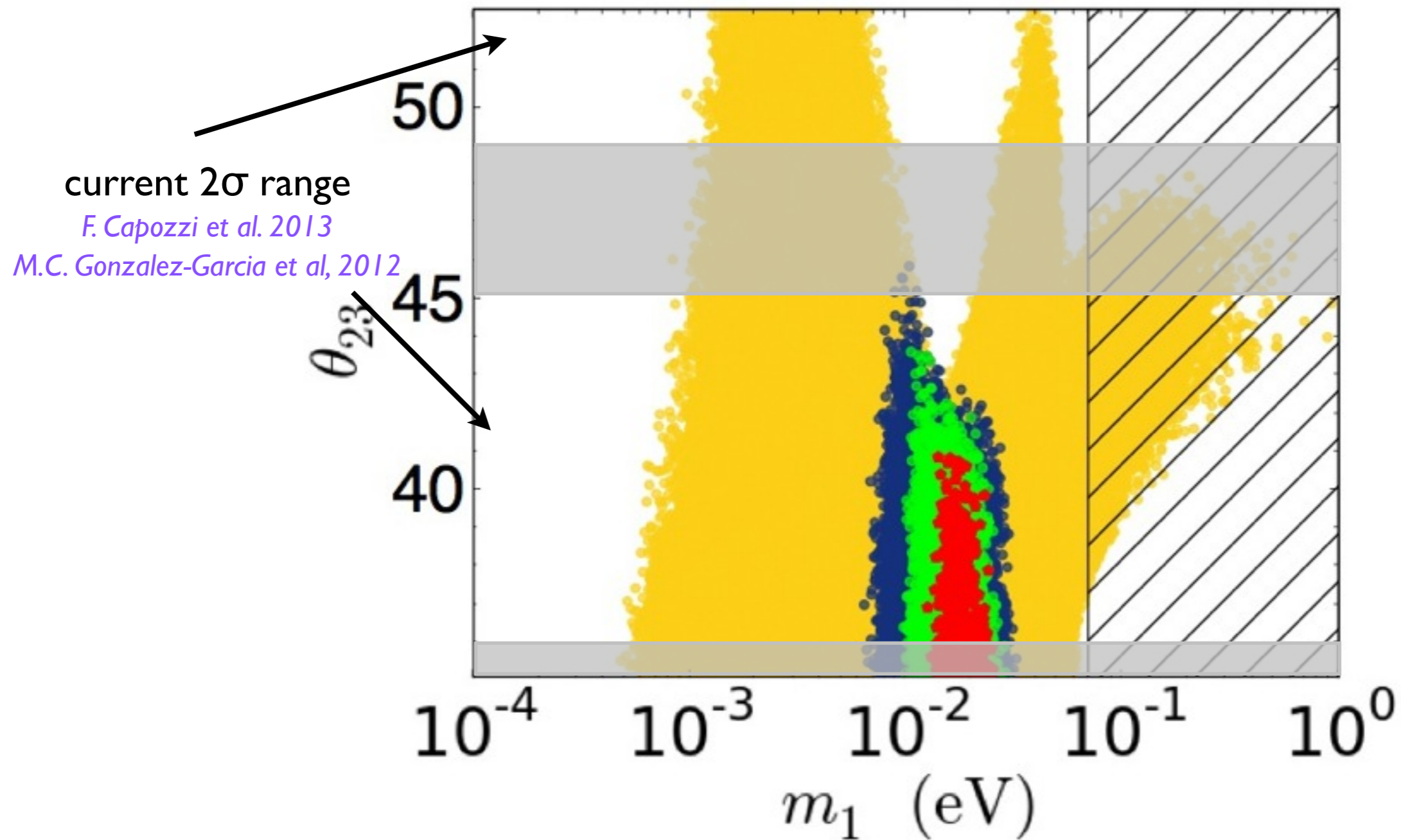


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Sharp upper bound $\theta_{23} \approx 45^\circ$ gives a clear prediction on the octant.

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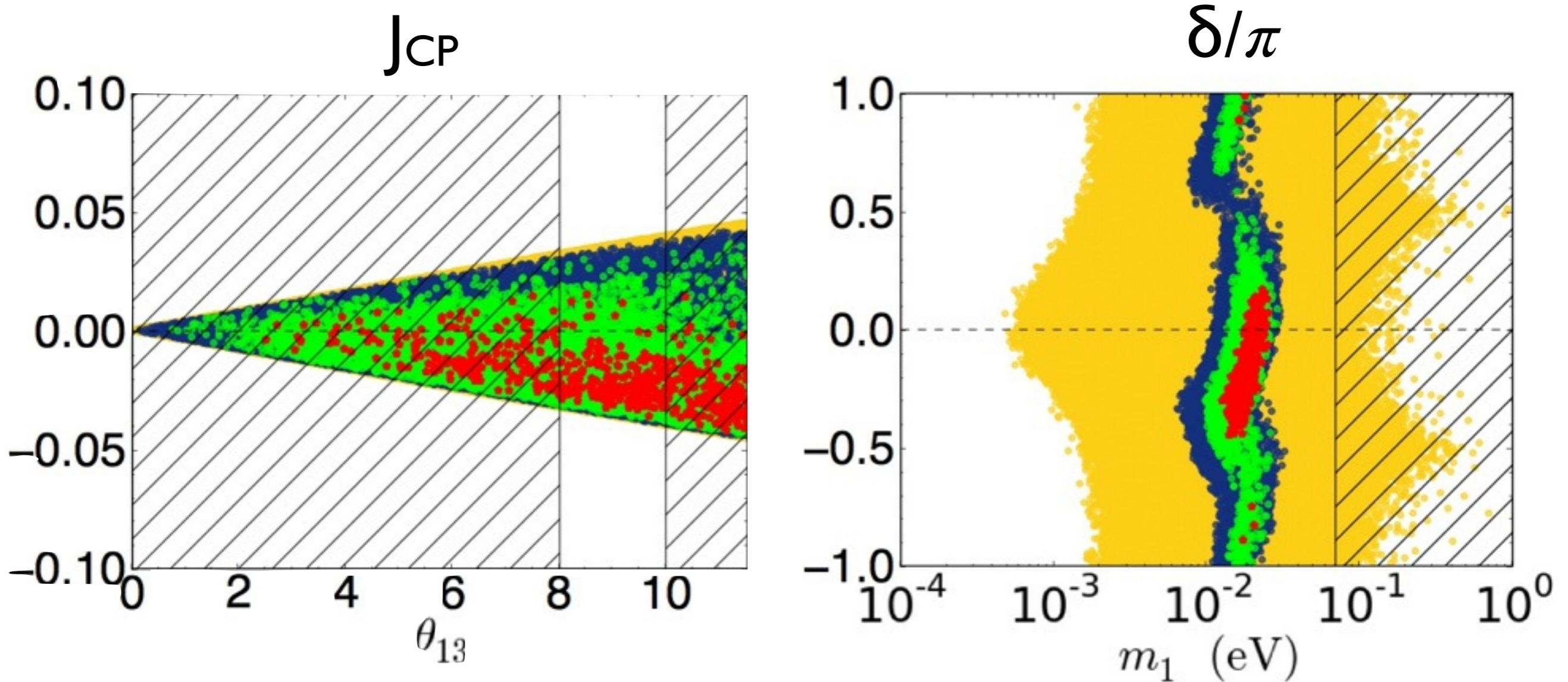
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- The Dirac phase and the Jarlskog invariant



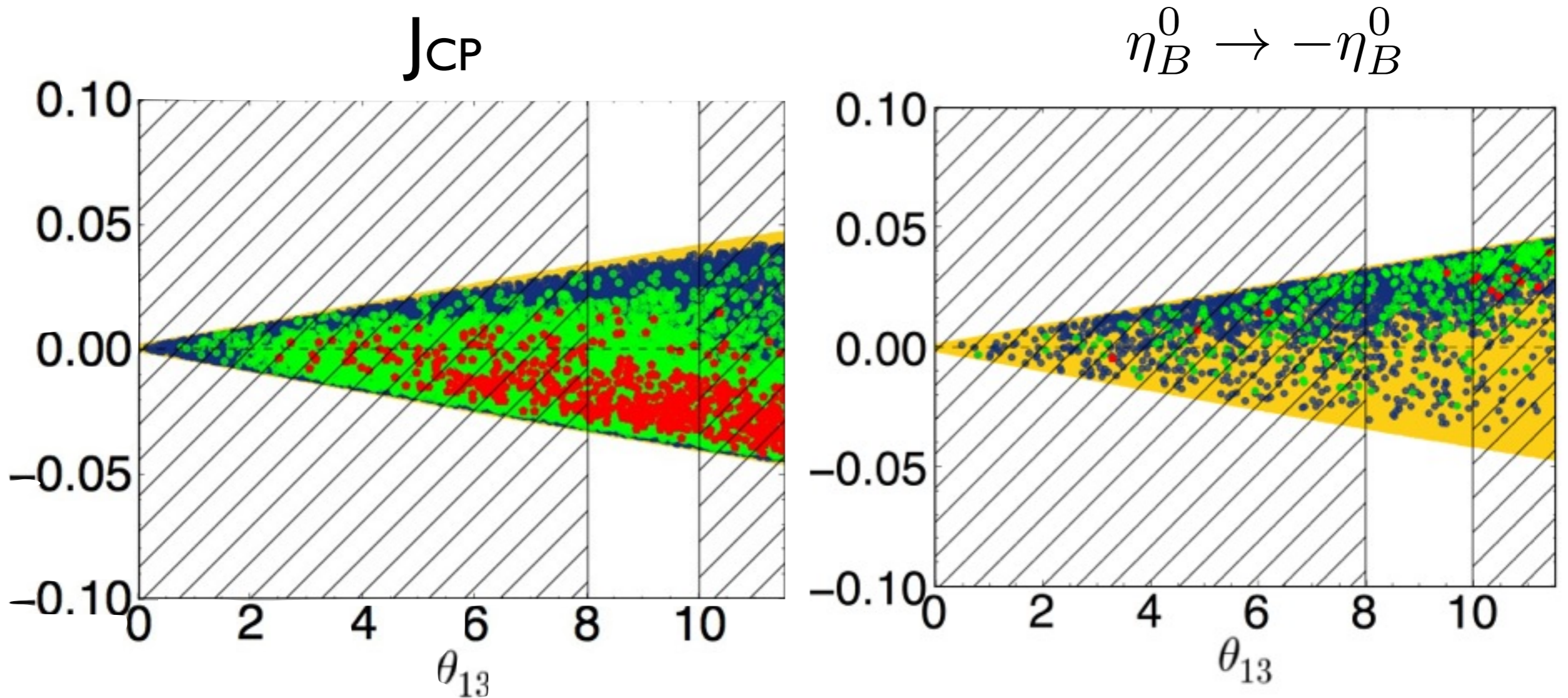
Net preference for $\delta < 0$, favourite by recent global analyses for $\theta_{23} \approx 45^\circ$

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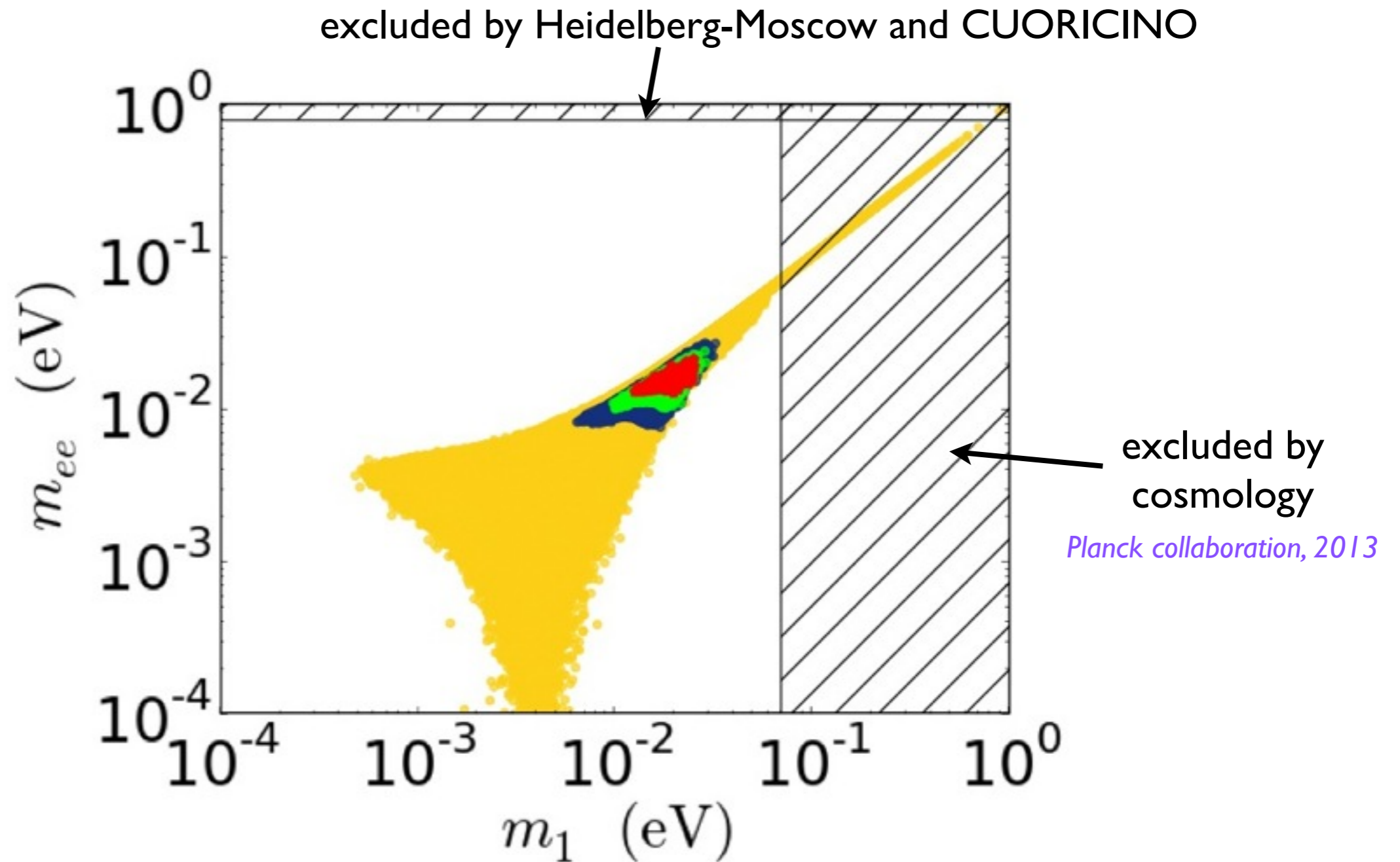
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- *The signature: light neutrino mass scales*

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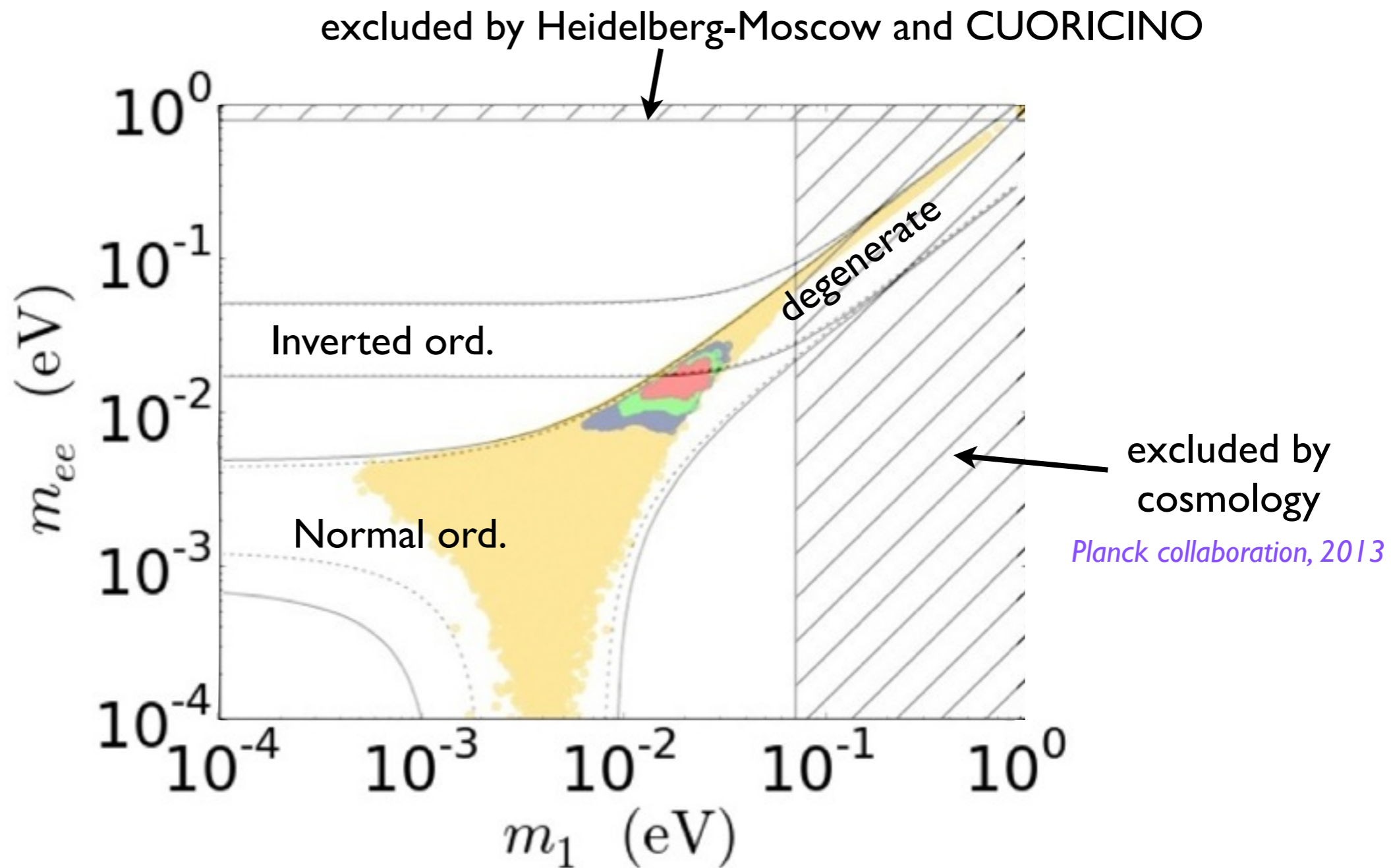


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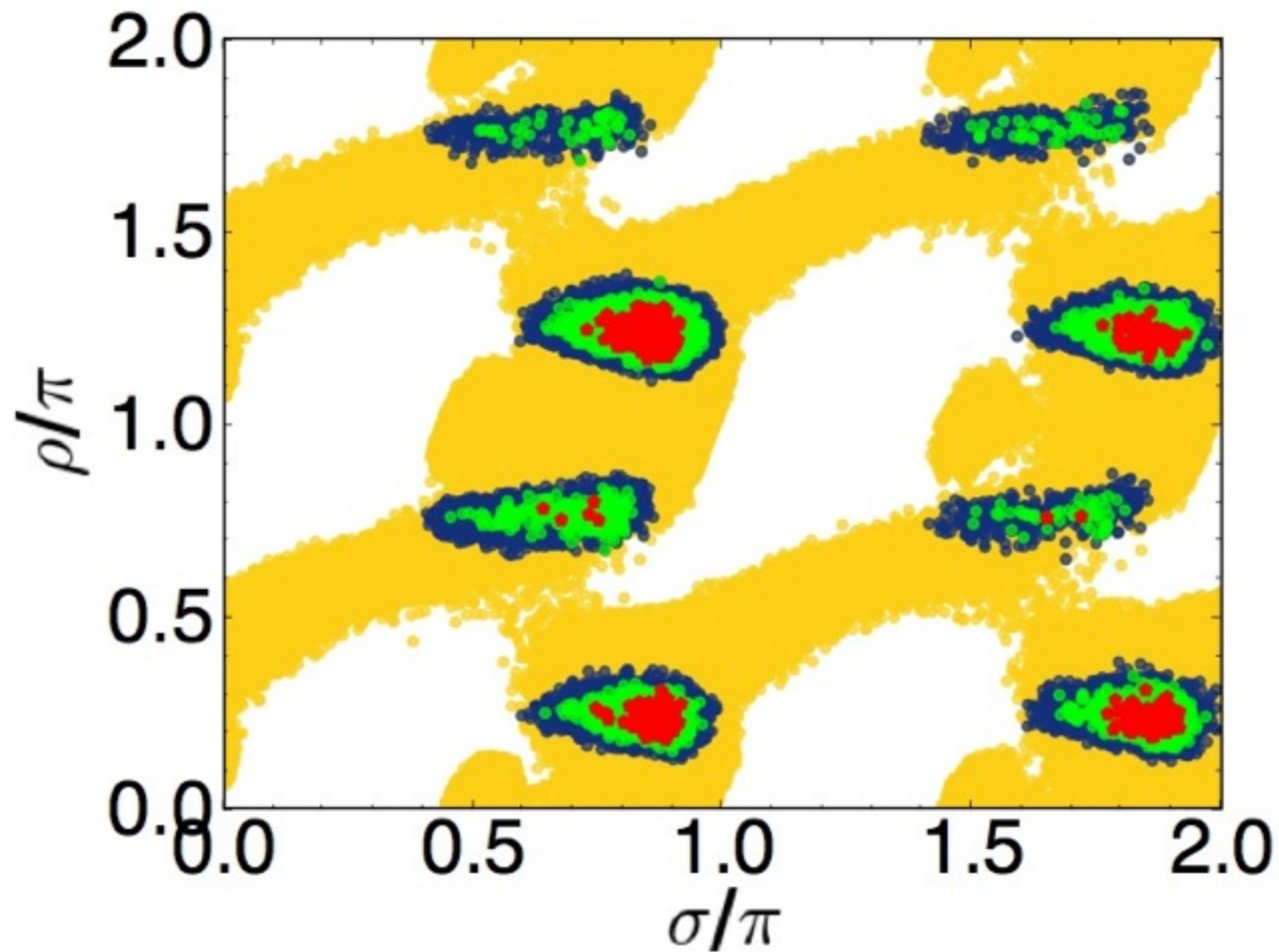


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- Majorana phases

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The Majorana phases are very constrained, explaining the trend

$$m_{ee} \approx m_1$$

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- What will happen if *strong thermal SO(10)-inspired solutions* are correct:

time ↓	$N_{B-L}^{p,i}$	10^{-1}	10^{-2}	✓ T2K, Daya Bay 2012
	θ_{13}	$\gtrsim 2^\circ$	$\gtrsim 0.5^\circ$	
	θ_{23}	$\lesssim 41^\circ$	$\lesssim 43^\circ$] ?? PINGU, T2K, NOvA
	ORDERING	NORMAL	NORMAL	
	δ	$-\pi/2 \div \pi/5$ $\simeq \pi$ (marginal, only for $\theta_{23} \lesssim 36^\circ$)	$\notin [0.4\pi, 0.7\pi]$	
	m_1	$(15 \div 25)$ meV	$(10 \div 30)$ meV	Cosmology ?
	m_{ee}	$\simeq 0.8 m_1 \simeq (12 \div 20)$ meV	$(8 \div 24)$ meV	next ² generation of $0\nu\beta\beta$ experiments

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- What happens if they are wrong:

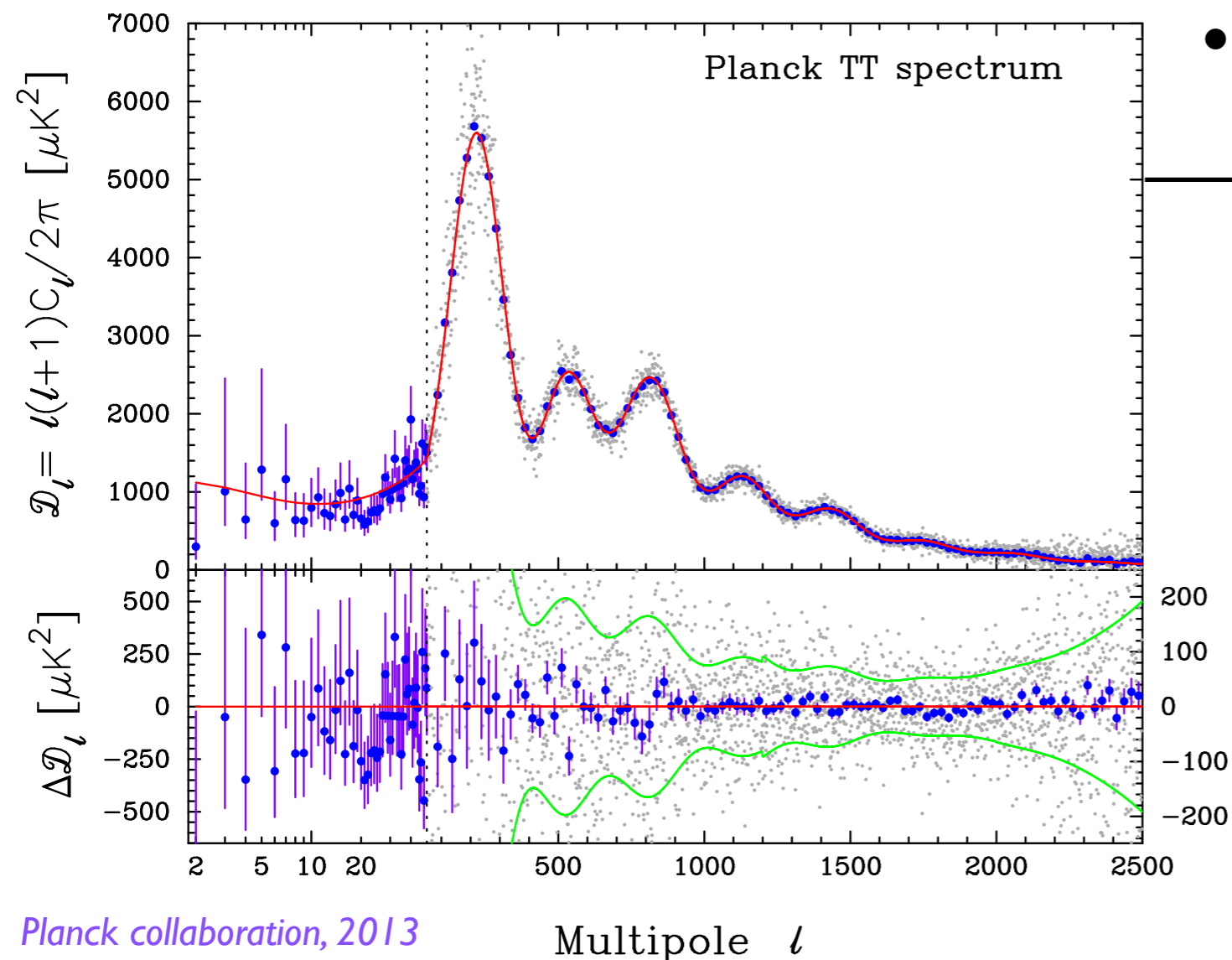
we falsified a simple, predictive and well-defined model of Leptogenesis!

Encore

The Baryon asymmetry

By analysing the Cosmic Microwave Background Radiation and the primordial abundances of elements we learn about the content of the Universe.

Fitting CMBR power spectrum:



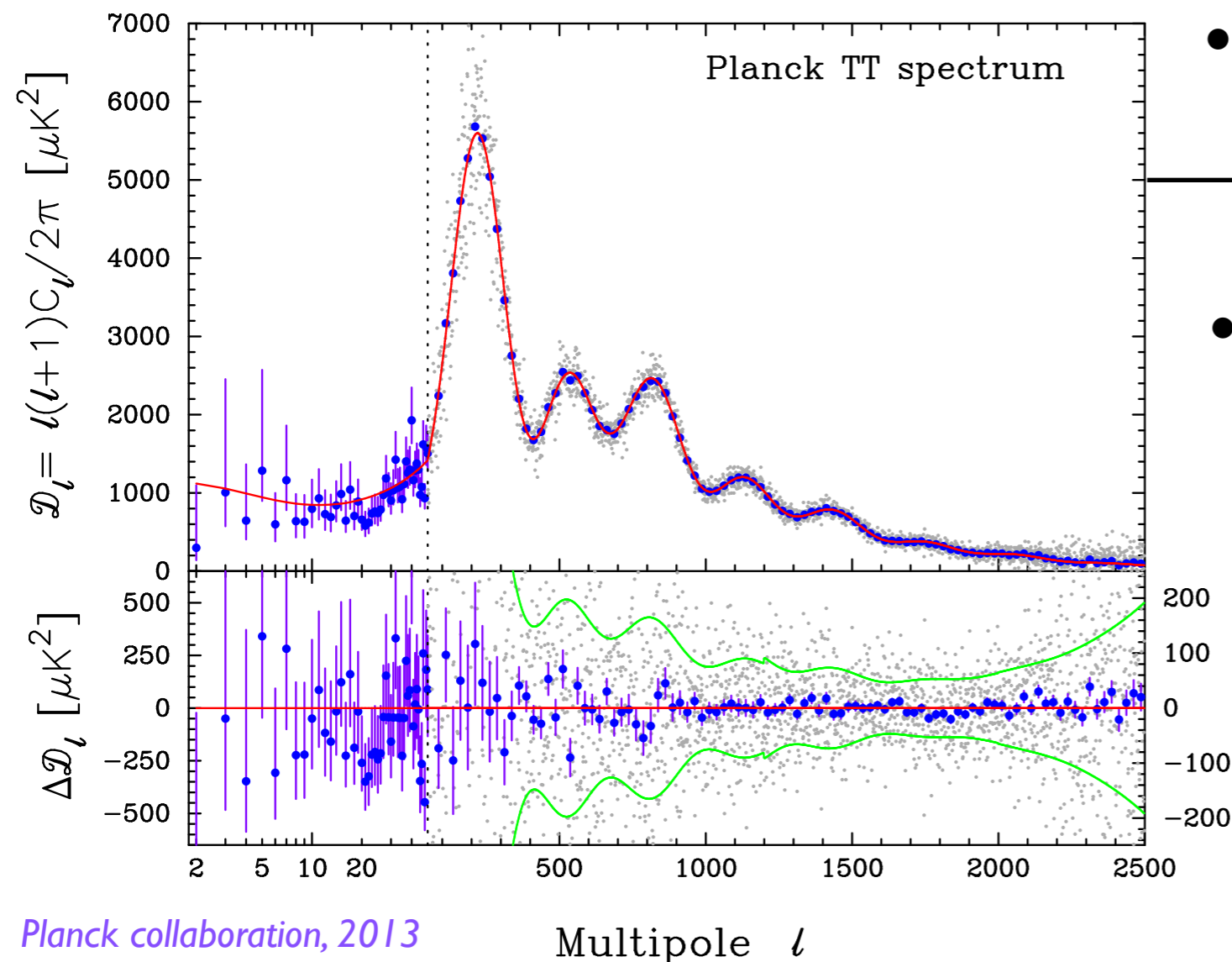
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$$\Omega_B h^2 \approx 0.02$$

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Fitting CMBR power spectrum:



- amount of baryons in the Universe:

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- No signs of primary antimatter on different scales imply $n_{\bar{B}} = 0$

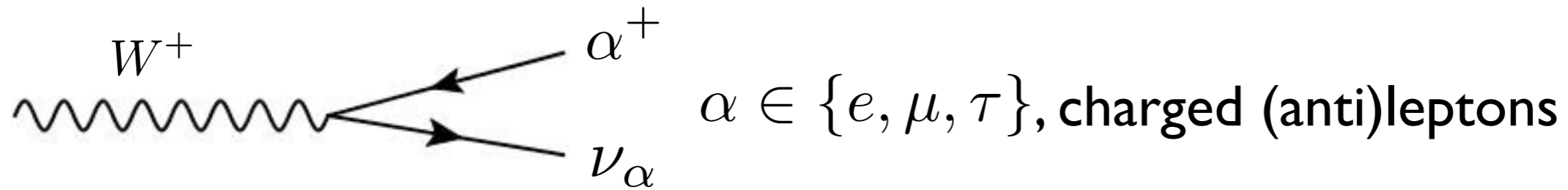
($n_X = \#$ density of X)

There is an asymmetry between matter and antimatter in our Universe

$$\eta_B := \frac{n_B - n_{\bar{B}}}{n_\gamma} \neq 0$$

Neutrino oscillations

Neutrinos are elusive particles that take part only in weak interactions. Up to now 3 kinds (*flavours*) of neutrino are known, named after the associated charged leptons involved in the interaction:



Suppose $\nu_\alpha \neq \nu_i$, with ν_i being the neutrino fields of the mass eigenstates, $i \in \{1, 2, 3\}$. Then *flavour neutrinos can be regarded as (coherent) superpositions of the latter*:

$$\nu_\alpha = U_{\alpha i} \nu_i \quad \longrightarrow \quad |\nu_\alpha\rangle = U_{\alpha i}^* |\nu_i\rangle, \quad U \text{ unitary matrix (PMNS mixing matrix)}$$

and the Schrödinger equations for the corresponding 1-particle states allow for *flavour oscillations*:

$$P_{\nu_\alpha \rightarrow \nu_\beta}(t) := |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{i,k=1}^3 U_{\beta i} U_{\alpha i}^* U_{\beta k}^* U_{\alpha k} e^{-\frac{\Delta m_{ik}^2 t}{2E}}, \quad \Delta m_{ik}^2 := m_i^2 - m_k^2$$

- Within the Standard Model neutrinos are described as massless leptons

$$\longrightarrow \Delta m_{ik}^2 = 0 \forall i, k \neq i \in \{1, 2, 3\}$$

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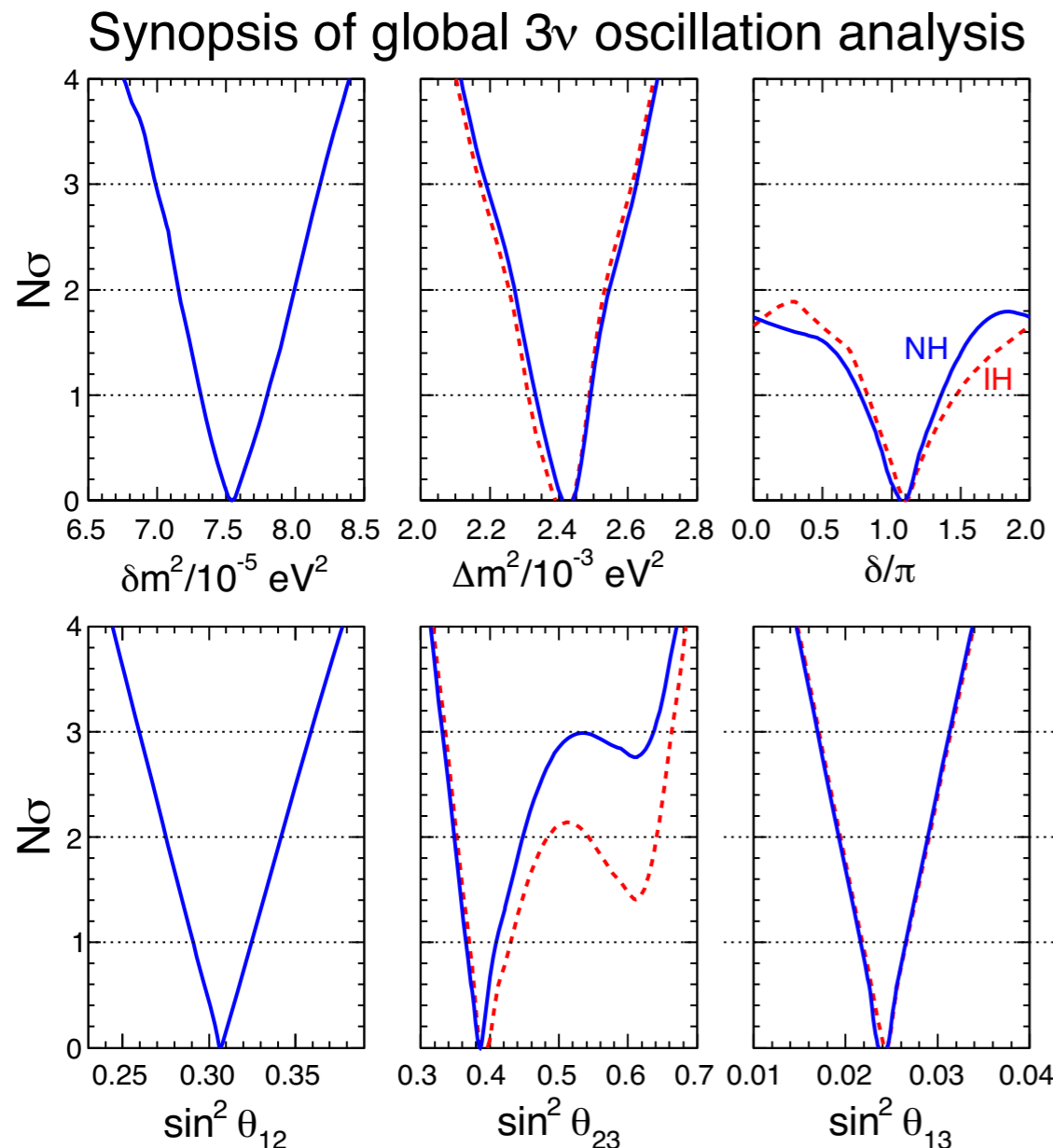
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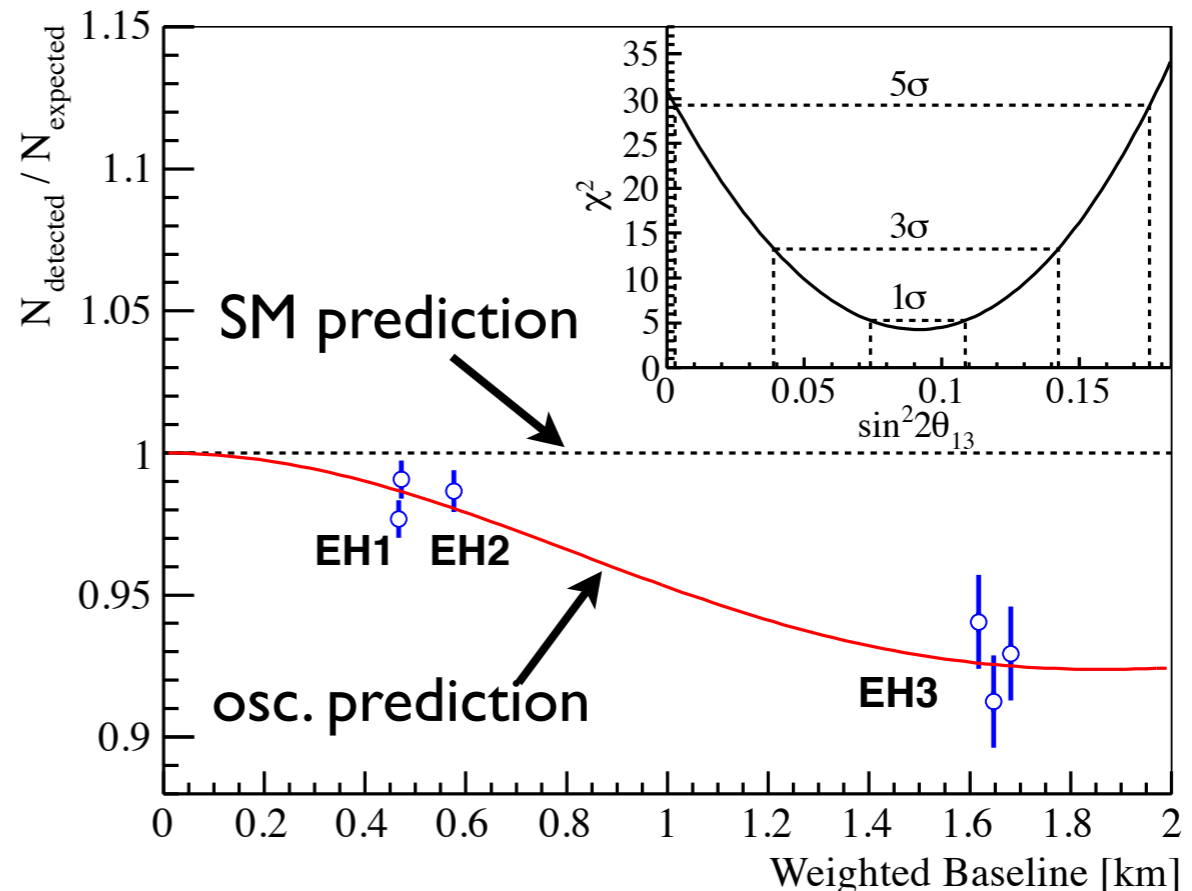
- Experimental status of neutrino oscillations: $\Delta m_{ik}^2 \neq 0!$



Neutrino mass puzzle: unknown origin of neutrino masses and mixing



G. I. Fogli et al., 2013



Daya Bay collaboration, 2012

A taste of N_1 Leptogenesis:

Consider only $N_1 - N_l$ Leptogenesis $z := M_1/T$

- N_1 abundance evolution, assuming $N_{N_1}(z=0) = 0$

$$\frac{dN_{N_1}}{dz} = -D_1 (N_{N_1} - N_{N_1}^{eq})$$

- Decays induce a B-L asymmetry abundance:

$$\frac{dN_{B-L}}{dz} = \epsilon_1 D_1 (N_{N_1} - N_{N_1}^{eq}) - W_1 N_{B-L}$$

$$D_i(z_i) := \frac{\Gamma_{D_i}(T) + \Gamma_{\bar{D}_i}(T)}{H z_i} \propto K_i$$

$$W_i(z_i) = \frac{1}{2} D_i(z_i) N_{N_1}^{eq}(z_i) \propto K_i$$

Decay efficiency parameter

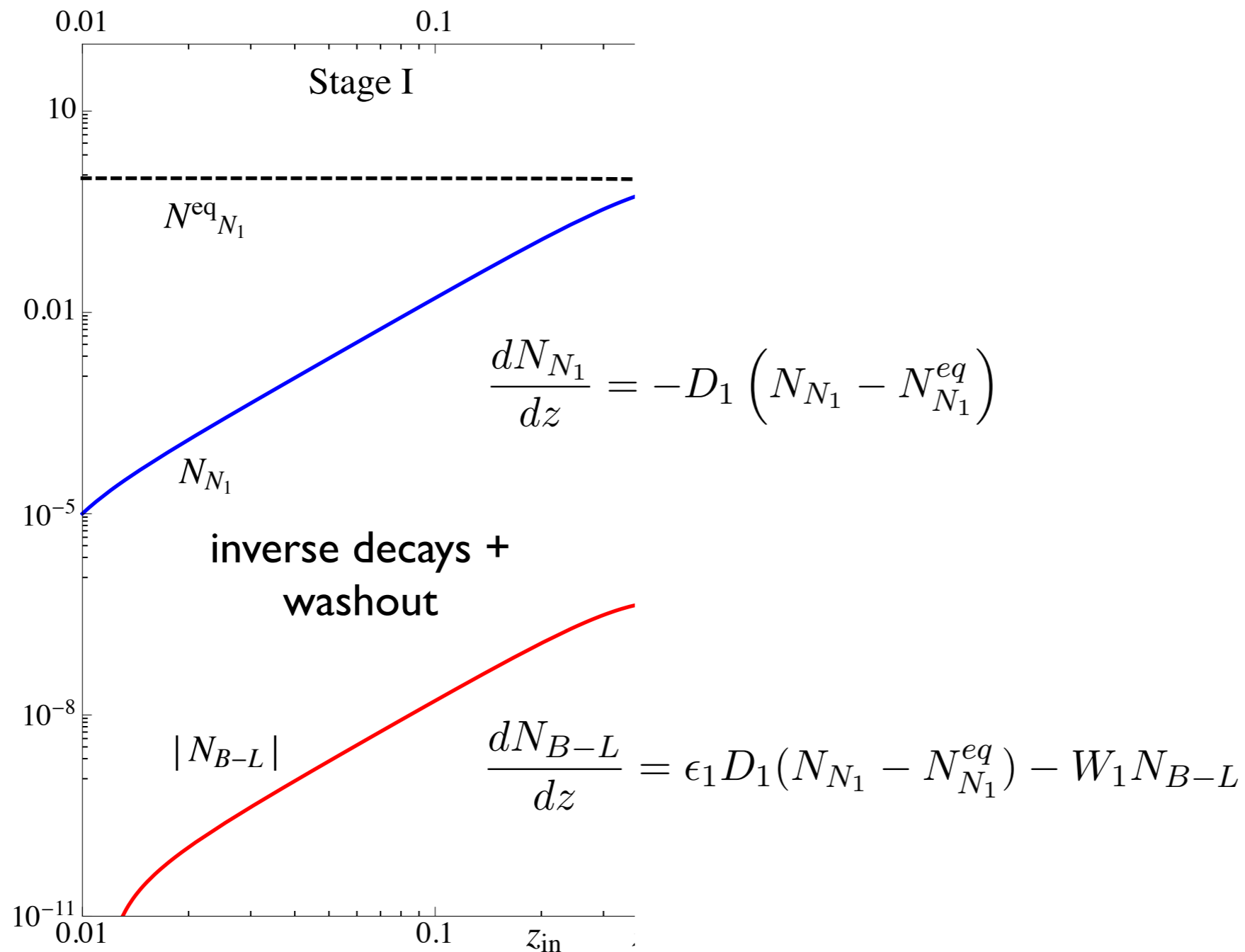
$$K_i := \frac{\Gamma_{D_i}(T=0) + \Gamma_{\bar{D}_i}(T=0)}{H(z_i=1)}$$

connection to low energy parameters

$$K_i \equiv \frac{\tilde{m}_i}{m_*} \quad \tilde{m}_i := \frac{(m_D^\dagger m_D)_{ii}}{M_i}$$

$$m_* := \frac{16\pi^{5/2} \sqrt{g_*}}{3\sqrt{5}} \frac{v^2}{M_{Pl}} \simeq 1.08 \times 10^{-3} \text{ eV}$$

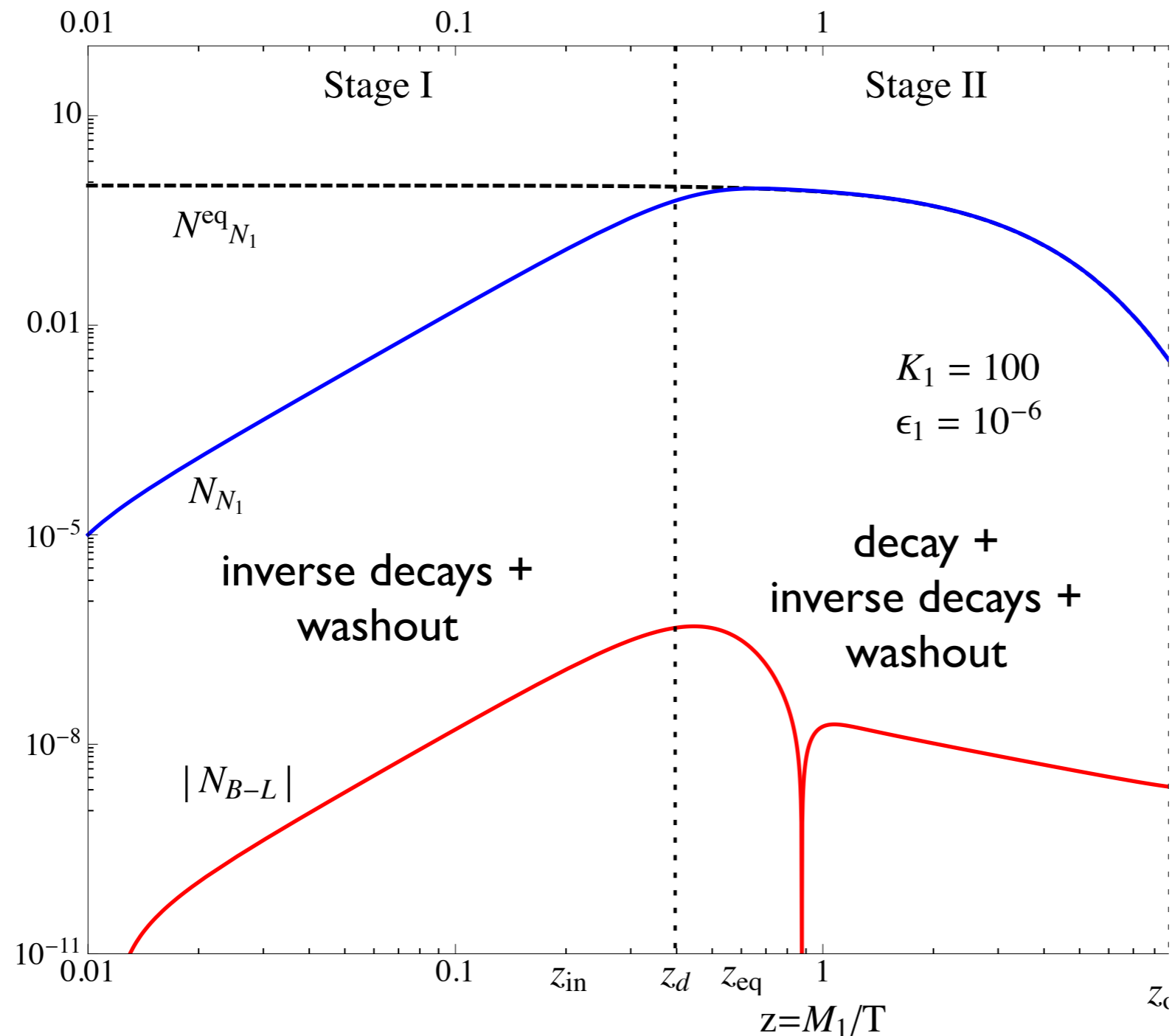
Focus on strong washout regime: $K_i \gg 1$



$$\frac{dN_{N_1}}{dz} = -D_1 (N_{N_1} - N_{N_1}^{eq})$$

$$\frac{dN_{B-L}}{dz} = \epsilon_1 D_1 (N_{N_1} - N_{N_1}^{eq}) - W_1 N_{B-L}$$

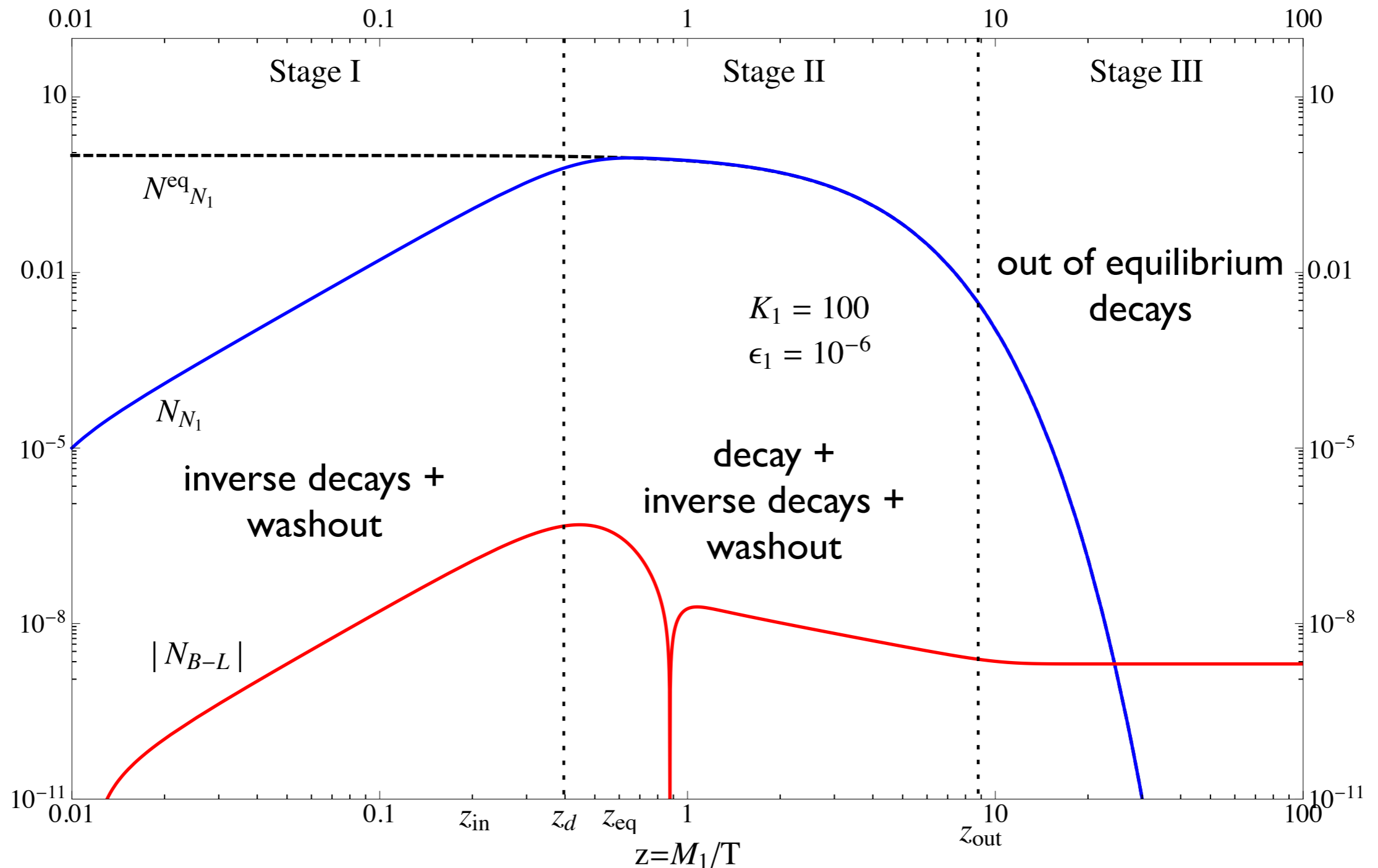
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N_2 -dominated leptogenesis:

- Multiple-stage Boltzmann equations; vanishing initial abundance:

– $T \sim M_3 > 10^{12}$ GeV: heavy flavour regime

N_3 processes are active...

$$\frac{dN_{\Delta 3}}{dz} = \epsilon_3 D_3 (N_{N_3} - N_{N_3}^{eq}) - W_3 N_{B-L}$$

...but CP asymmetry is negligible: $\epsilon \sim (M_2/M_3)^2$

$\epsilon_3 \simeq 0 \longrightarrow N_{\Delta 3} = 0$ *no B-L asymmetry produced*

– $T \sim M_2 < 10^{12}$ GeV \wedge $M_2 > 10^9$ GeV: two-flavour regime

N_2 processes generate a B-L asymmetry ($\beta = \tau, \tau_2^\perp$)

$$\frac{dN_{\Delta 2}}{dz} = \sum_{\beta} \frac{dN_{\Delta \beta}^{(2)}}{dz} \quad \frac{dN_{\Delta \beta}^{(2)}}{dz} = \epsilon_{2\beta} D_2 (N_{N_2} - N_{N_2}^{eq}) - p_{2\beta} W_2 N_{B-L}$$

therefore:

$$N_{\Delta 2}(T < M_2) = \epsilon_{2\tau} \kappa(K_2, K_{2\tau}) + \epsilon_{2\tau_2^\perp} \kappa(K_2, K_{2\tau_2^\perp})$$

$$\epsilon_i = \frac{\Gamma(N_i \rightarrow l\phi) - \Gamma(N_i \rightarrow \bar{l}\bar{\phi})}{\Gamma(N_i \rightarrow l\phi) + \Gamma(N_i \rightarrow \bar{l}\bar{\phi})} \quad \epsilon_2 \propto M_2 \propto \alpha_2^2$$

$$K_i \equiv \frac{\tilde{m}_i}{m_*} \quad K_{i\gamma} := p_{i\gamma} K_i \quad \epsilon_{i\gamma} := p_{i\gamma} \epsilon_i \quad p_{i\gamma} := \frac{|(m_D)_{\gamma i}|^2}{(m_D^\dagger m_D)_{ii}}$$

$-T \sim M_1 < 10^9$ GeV: three-flavour regime

($\alpha = e, \mu, \tau$)

N_1 processes are active; no B-L asymmetry generated as

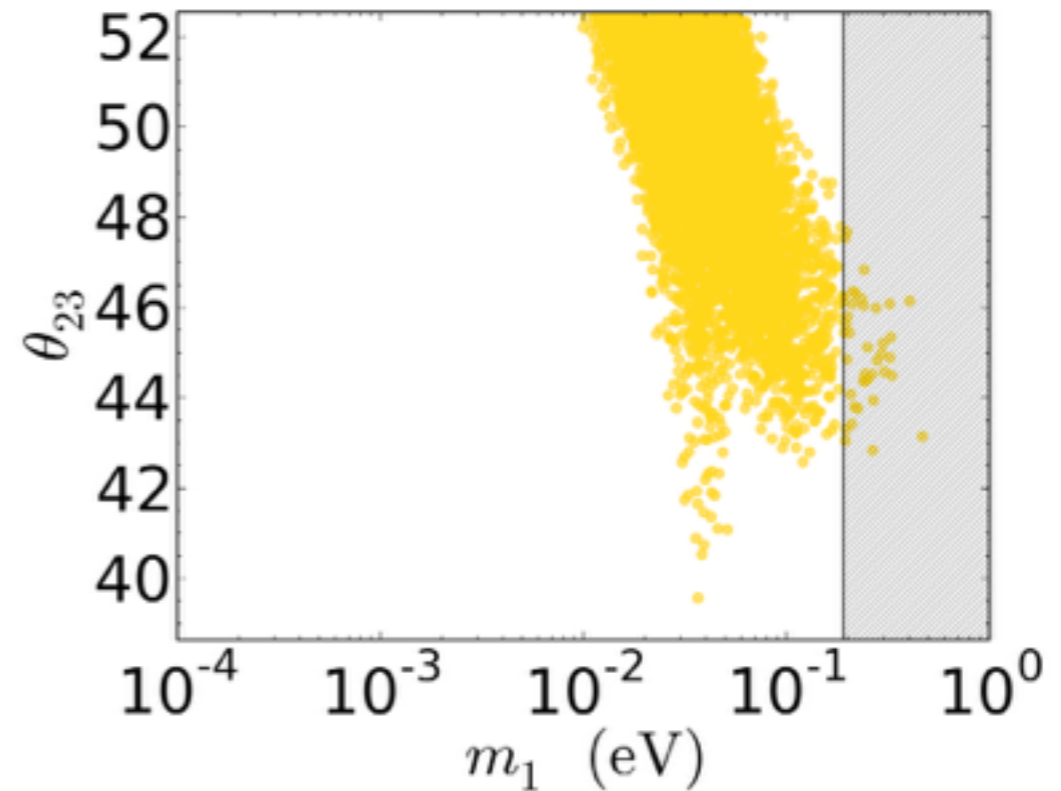
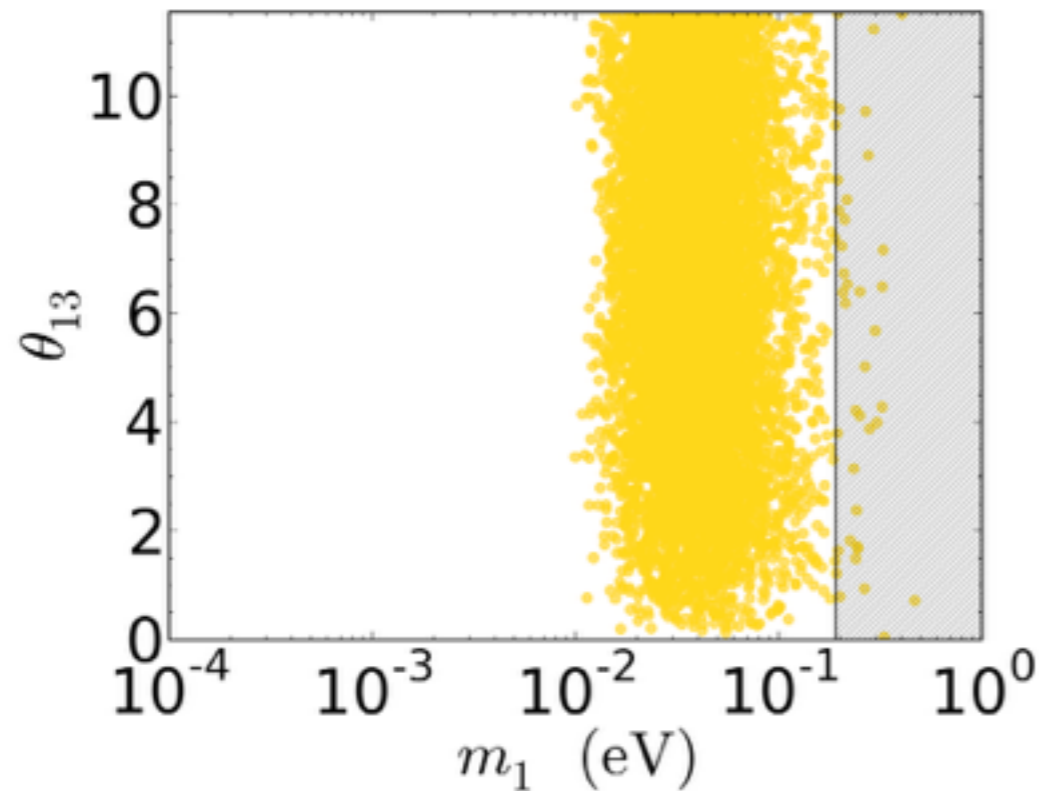
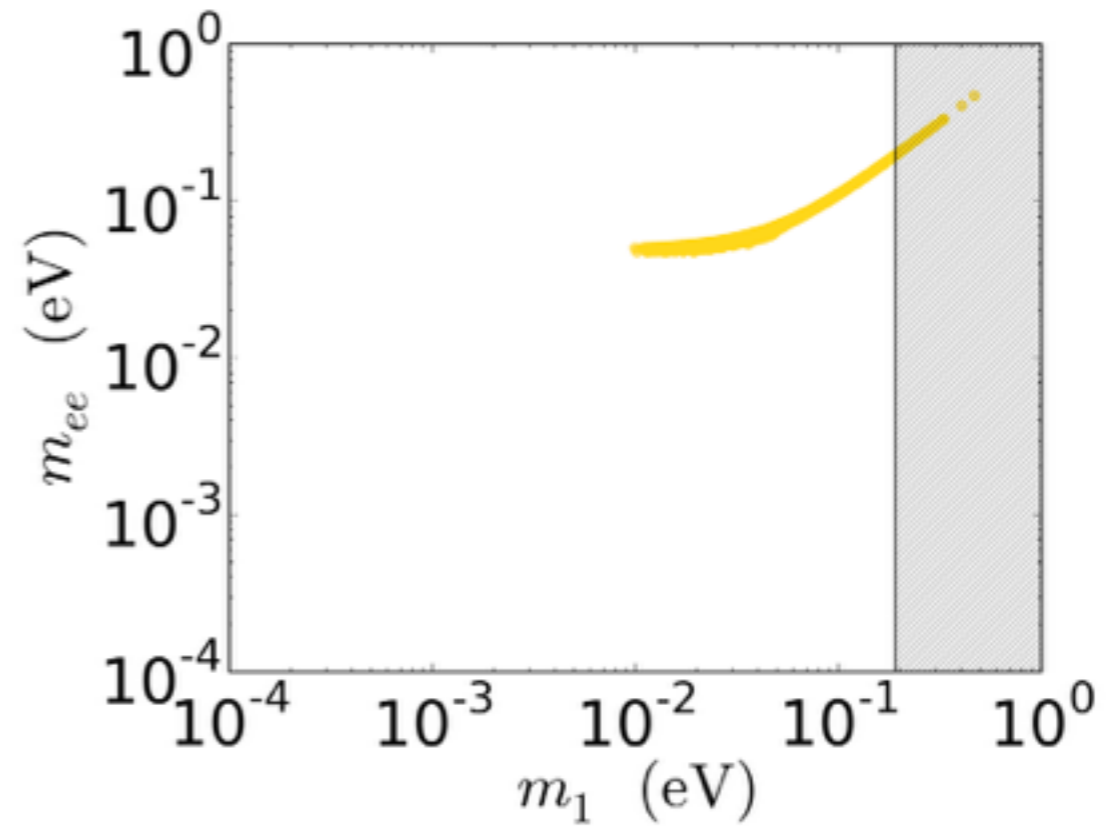
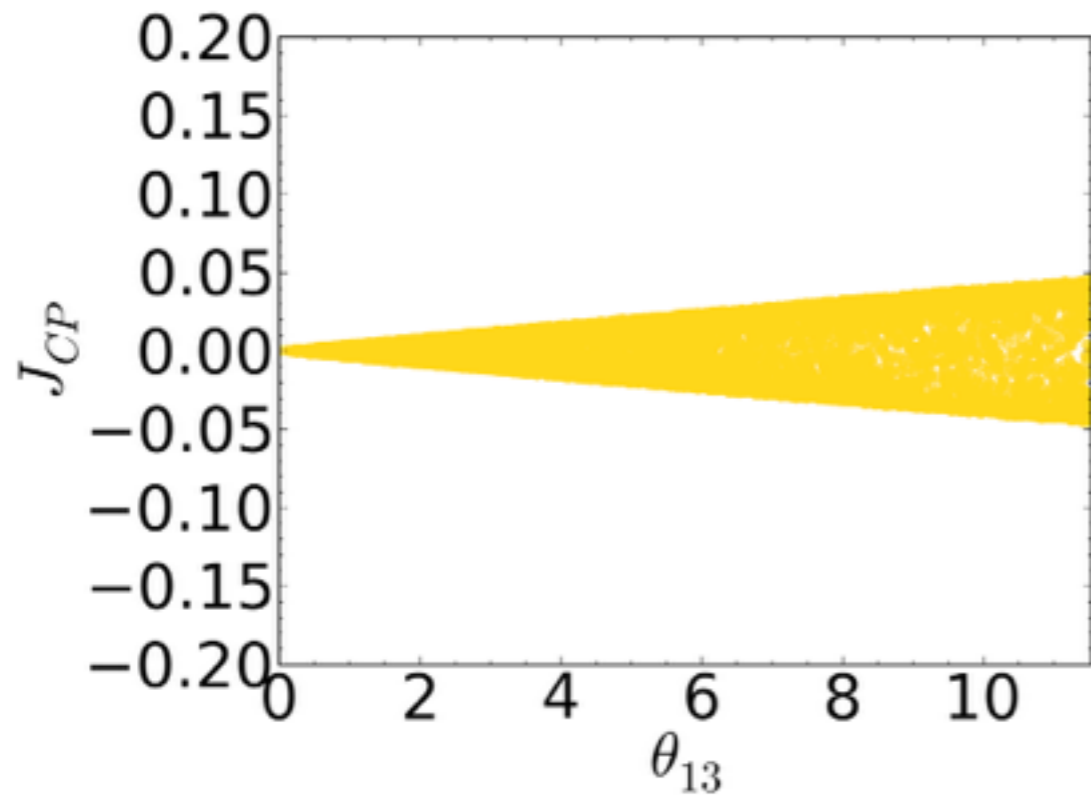
$$M_1 < 10^9 \text{ GeV} \quad \epsilon_1 \simeq 0 \quad (\text{Davidson - Ibarra bound})$$

N_2 asymmetry is washed out: $\frac{dN_{\Delta\alpha}^{(1)}}{dz} = -p_{1\alpha} W_1 p_{2\alpha} N_{\Delta 2}$

$$N_{B-L}^{lep,f} := \sum_{\alpha} N_{\Delta\alpha}^{(1)}(T \ll M_1) \simeq \frac{p_{2e}}{p_{2\tau_2^\perp}} \epsilon_{2\tau_2^\perp} \kappa(K_2, K_{2\tau_2^\perp}) e^{-\frac{3\pi}{8} K_{1e}} +$$

$$+ \frac{p_{2\mu}}{p_{2\tau_2^\perp}} \epsilon_{2\tau_2^\perp} \kappa(K_2, K_{2\tau_2^\perp}) e^{-\frac{3\pi}{8} K_{1\mu}} + \epsilon_{2\tau} \kappa(K_2, K_{2\tau}) e^{-\frac{3\pi}{8} K_{1\tau}}$$

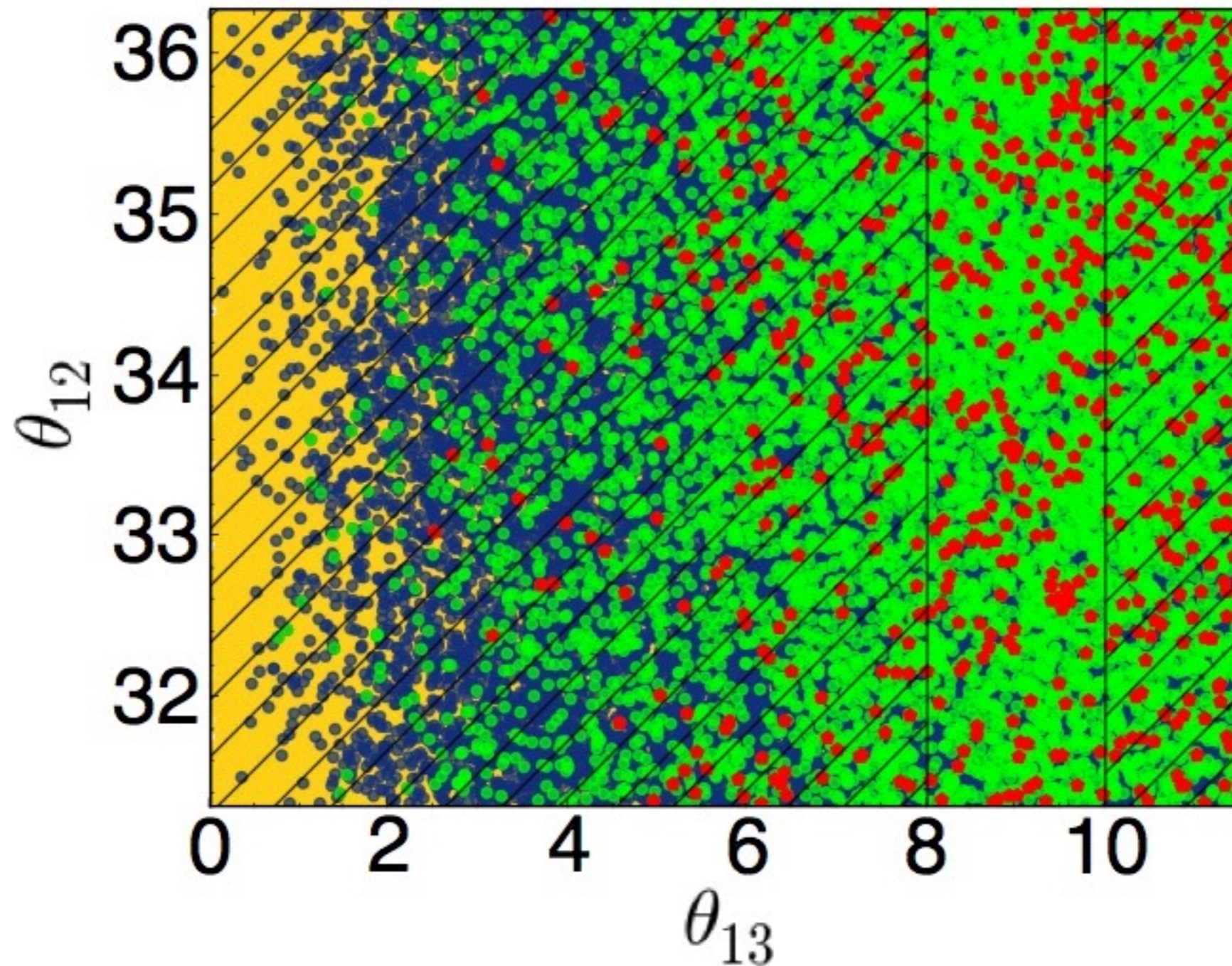
- About inverter ordering: no Strong Leptogenesis



- θ_{12} in the SO(10)-inspired models: strong thermal solutions

$$N_{B-L}^{preex,0} = 0, 10^{-3}, 10^{-2}, 10^{-1}$$

$$N_{B-L}^{preex,f} < 10^{-8}$$



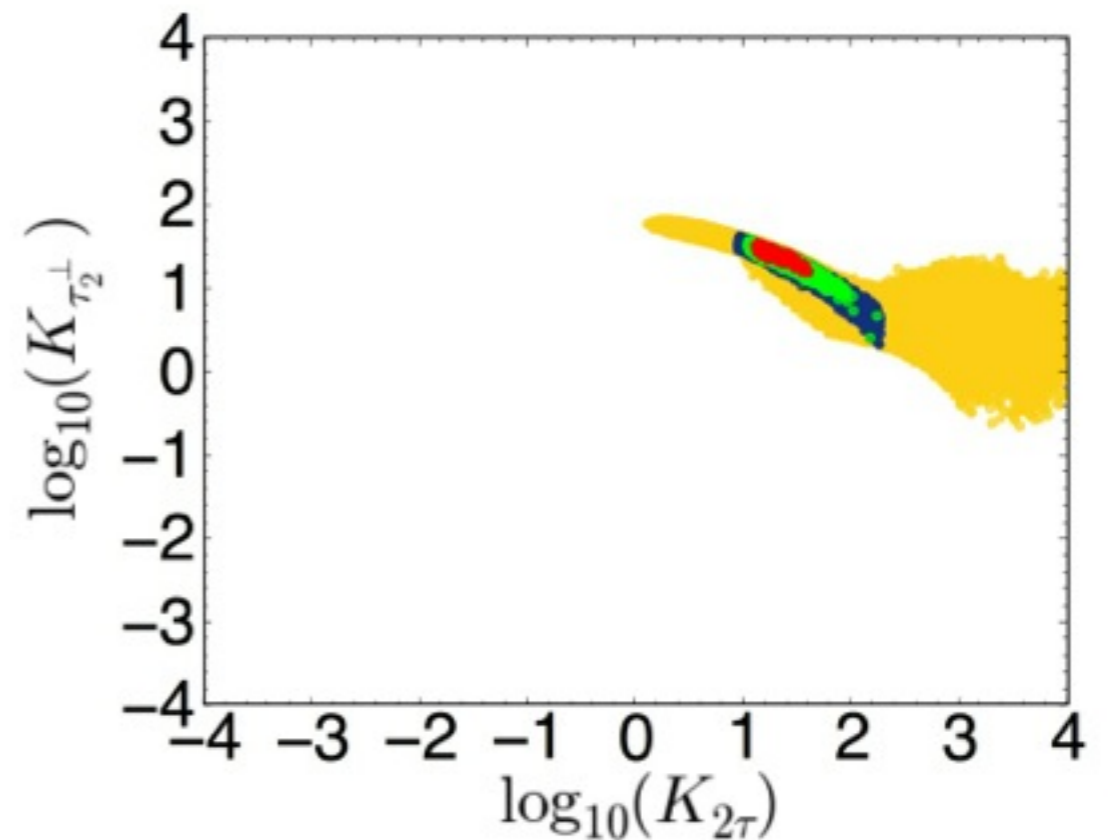
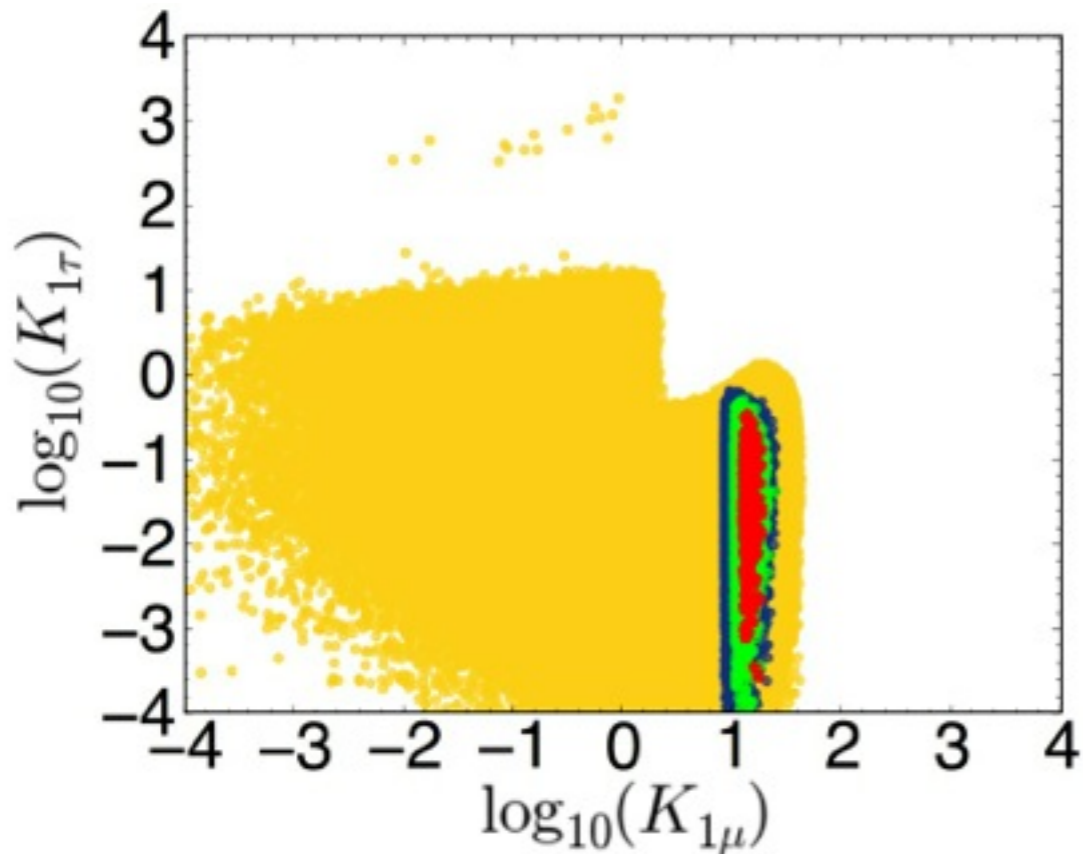
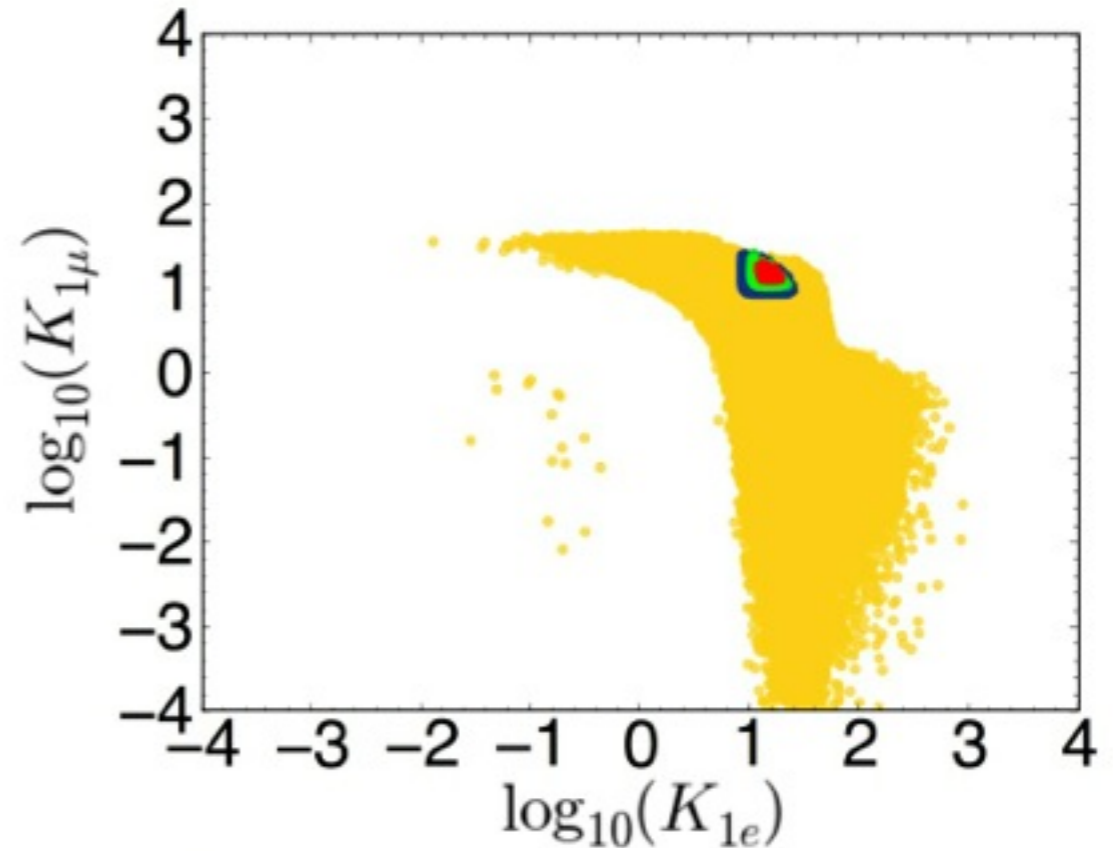
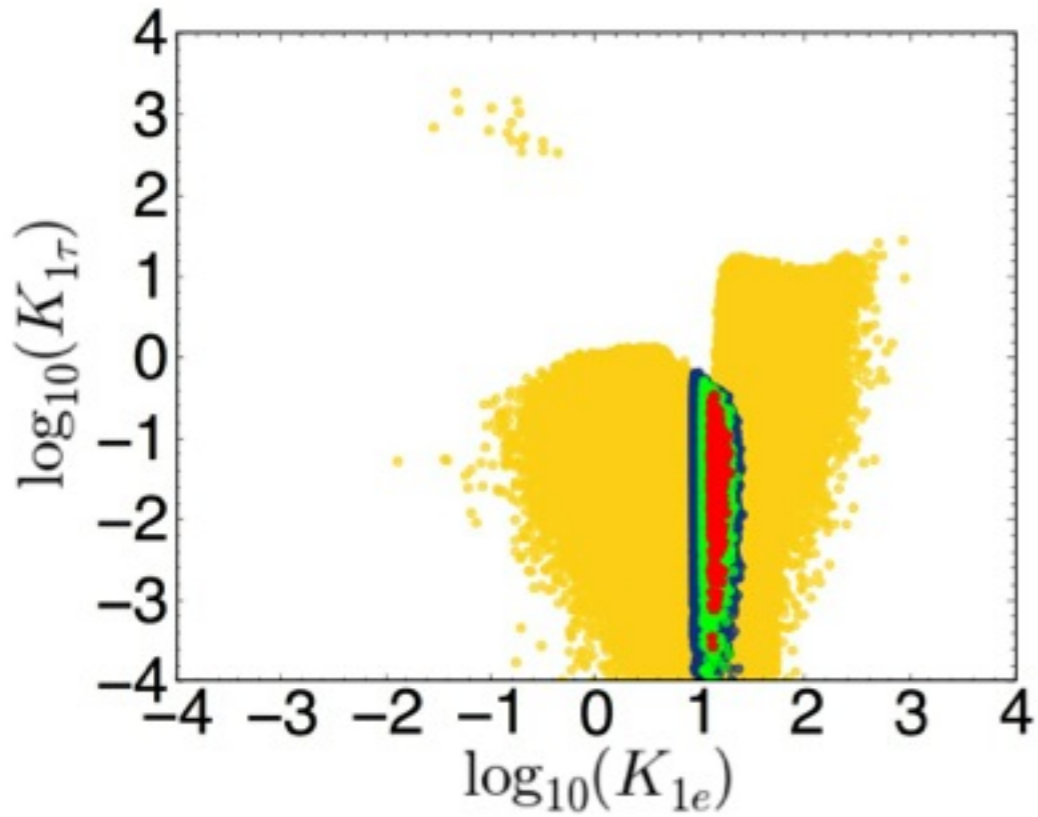
● Decay efficiency parameters:

$$N_{B-L}^{preex,0} = 0, 10^{-3}, 10^{-2}, 10^{-1}$$

$$N_{B-L}^{preex,f} < 10^{-8}$$

- N_2 -dominated Leptogenesis in strong washout regime ($K_2 \gg 1$)

- Asymmetric washout from N_1 ($K_{1e}, K_{1\mu} \gg 1; K_{1\tau} \sim 1$)



● Status of neutrino parameters

M.C. Gonzalez-Garcia et al, 2012

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \rightarrow 0.344$	$0.311^{+0.013}_{-0.013}$	$0.273 \rightarrow 0.354$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \rightarrow 35.89$	$33.87^{+0.82}_{-0.80}$	$31.52 \rightarrow 36.49$
$\sin^2 \theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \rightarrow 0.667$	$0.416^{+0.036}_{-0.029} \oplus 0.600^{+0.019}_{-0.026}$	$0.341 \rightarrow 0.670$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \rightarrow 54.8$	$40.1^{+2.1}_{-1.6} \oplus 50.7^{+1.2}_{-1.5}$	$35.7 \rightarrow 55.0$
$\sin^2 \theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \rightarrow 0.0299$	$0.0255^{+0.0024}_{-0.0024}$	$0.0181 \rightarrow 0.0327$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \rightarrow 9.96$	$9.20^{+0.41}_{-0.45}$	$7.73 \rightarrow 10.42$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \rightarrow 360$	298^{+59}_{-145}	$0 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \rightarrow 8.09$	$7.51^{+0.21}_{-0.15}$	$7.04 \rightarrow 8.12$
$\frac{\Delta m_{31}^2}{10^{-3} \text{ eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \rightarrow +2.695$	$+2.489^{+0.055}_{-0.051}$	$+2.294 \rightarrow +2.715$
$\frac{\Delta m_{32}^2}{10^{-3} \text{ eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \rightarrow -2.242$	$-2.468^{+0.073}_{-0.065}$	$-2.678 \rightarrow -2.252$

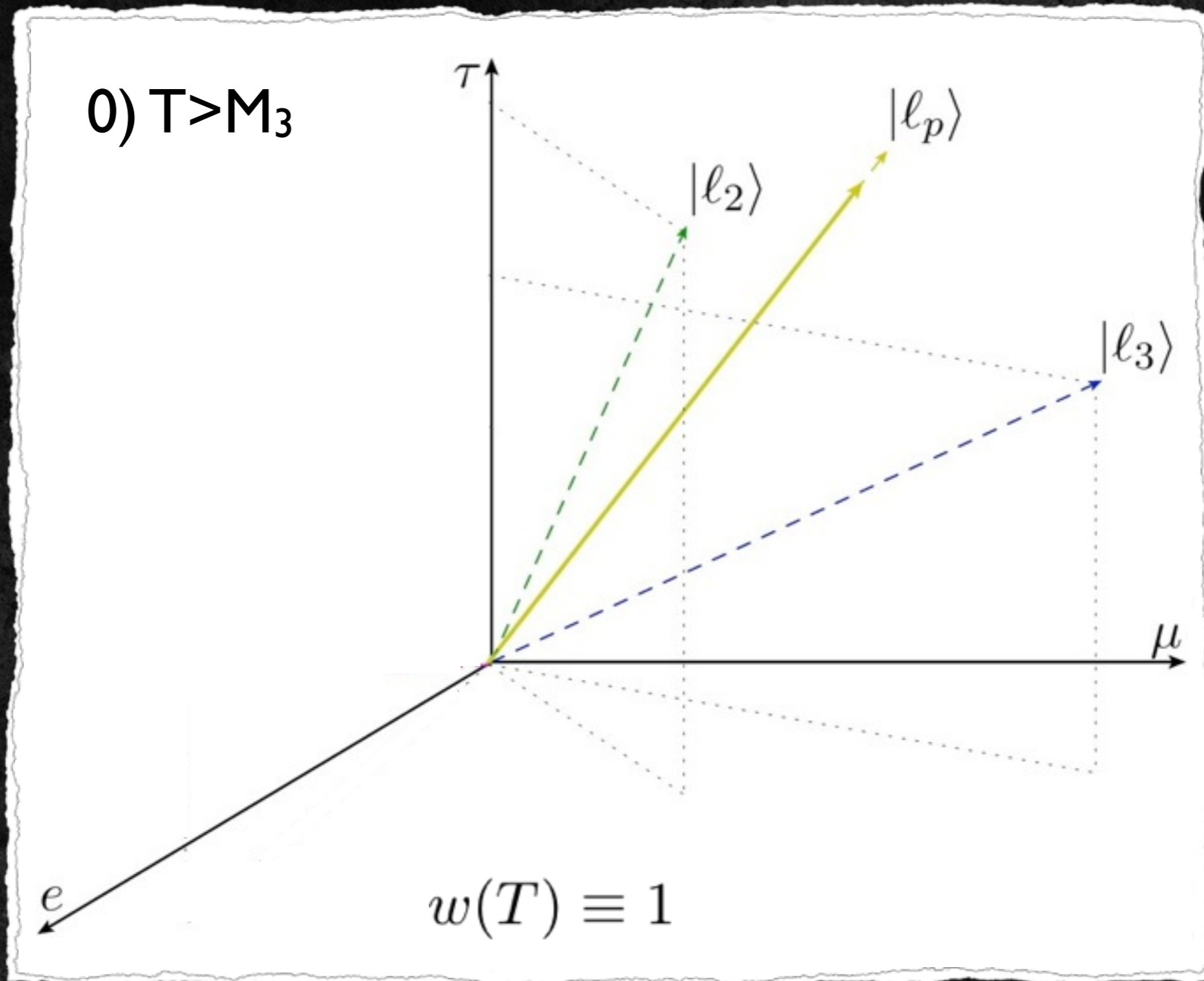
Table 1. Three-flavour oscillation parameters from our fit to global data after the Neutrino 2012 conference. For “Free Fluxes + RSBL” reactor fluxes have been left free in the fit and short baseline reactor data (RSBL) with $L \lesssim 100$ m are included; for “Huber Fluxes, no RSBL” the flux prediction from [42] are adopted and RSBL data are not used in the fit.

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi_{\text{I-N}}^2 = -0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV ² (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2 \theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV ² (NH)	2.43	2.37 – 2.49	2.30 – 2.55	2.23 – 2.61
$\Delta m^2/10^{-3}$ eV ² (IH)	2.38	2.32 – 2.44	2.25 – 2.50	2.19 – 2.56
$\sin^2 \theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54	1.95 – 2.74	1.76 – 2.95
$\sin^2 \theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59	1.98 – 2.79	1.78 – 2.98
$\sin^2 \theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70	3.93 – 5.52	3.74 – 6.26
$\sin^2 \theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94	4.00 – 6.20	3.80 – 6.41
δ/π (NH)	1.39	1.12 – 1.77	0.00 – 0.16 \oplus 0.86 – 2.00	—
δ/π (IH)	1.31	0.98 – 1.60	0.00 – 0.02 \oplus 0.70 – 2.00	—

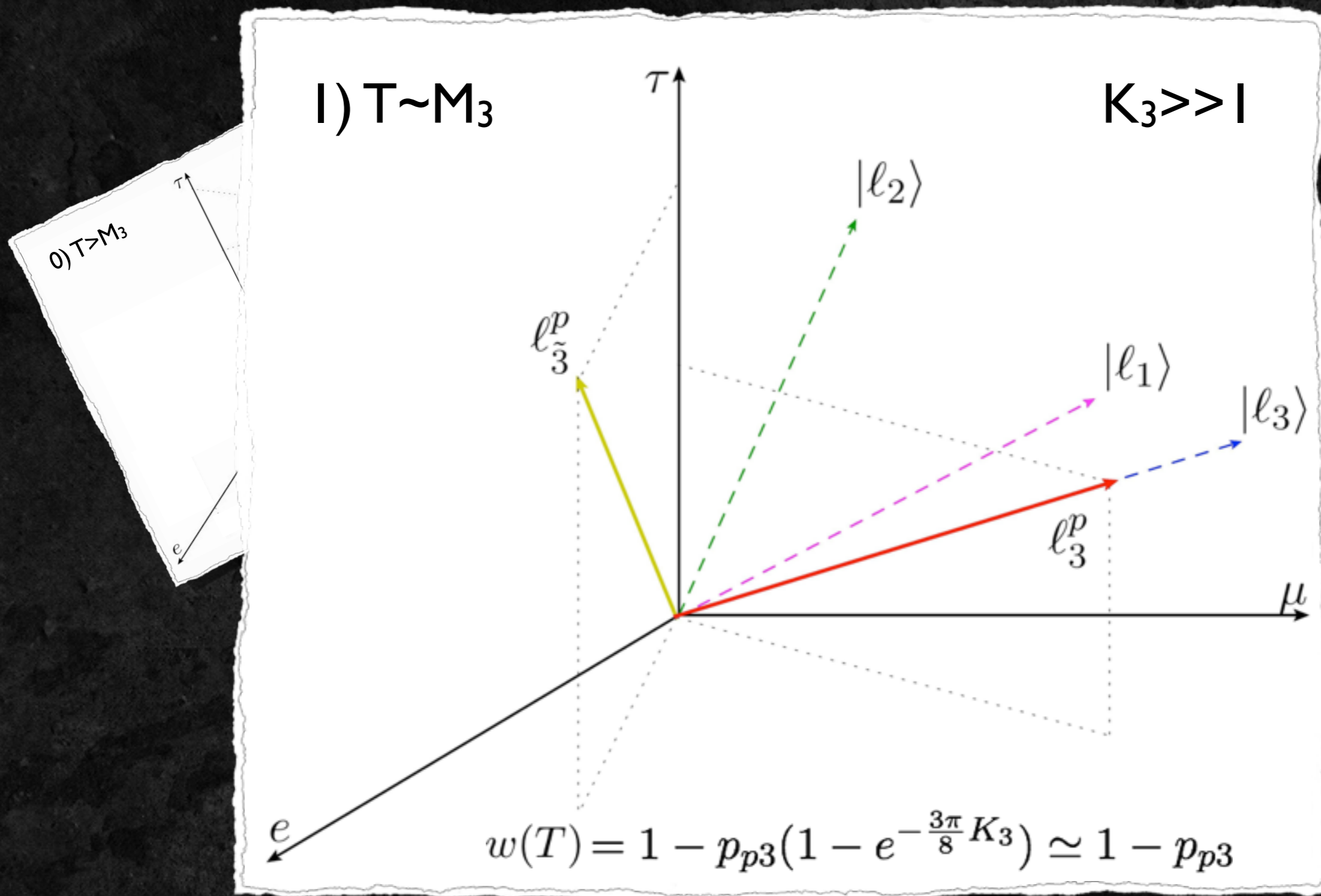
The τ - N_2 scenario step by step

The τ - N_2 scenario step by step



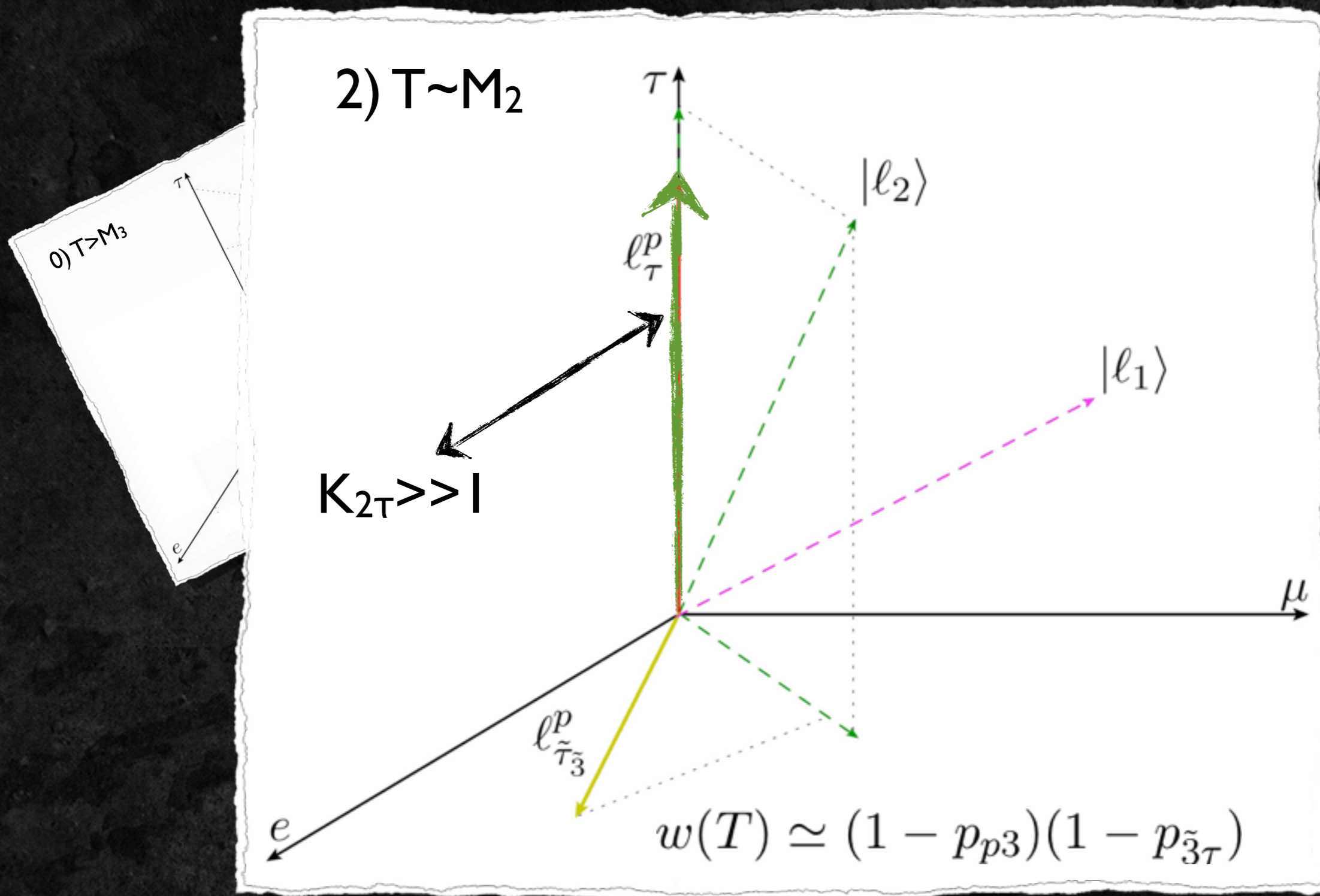
Before Leptogenesis' onset. Preexisting leptons in yellow

The τ - N_2 scenario step by step



N_{R3} 's processes are active. Components in red are washed out

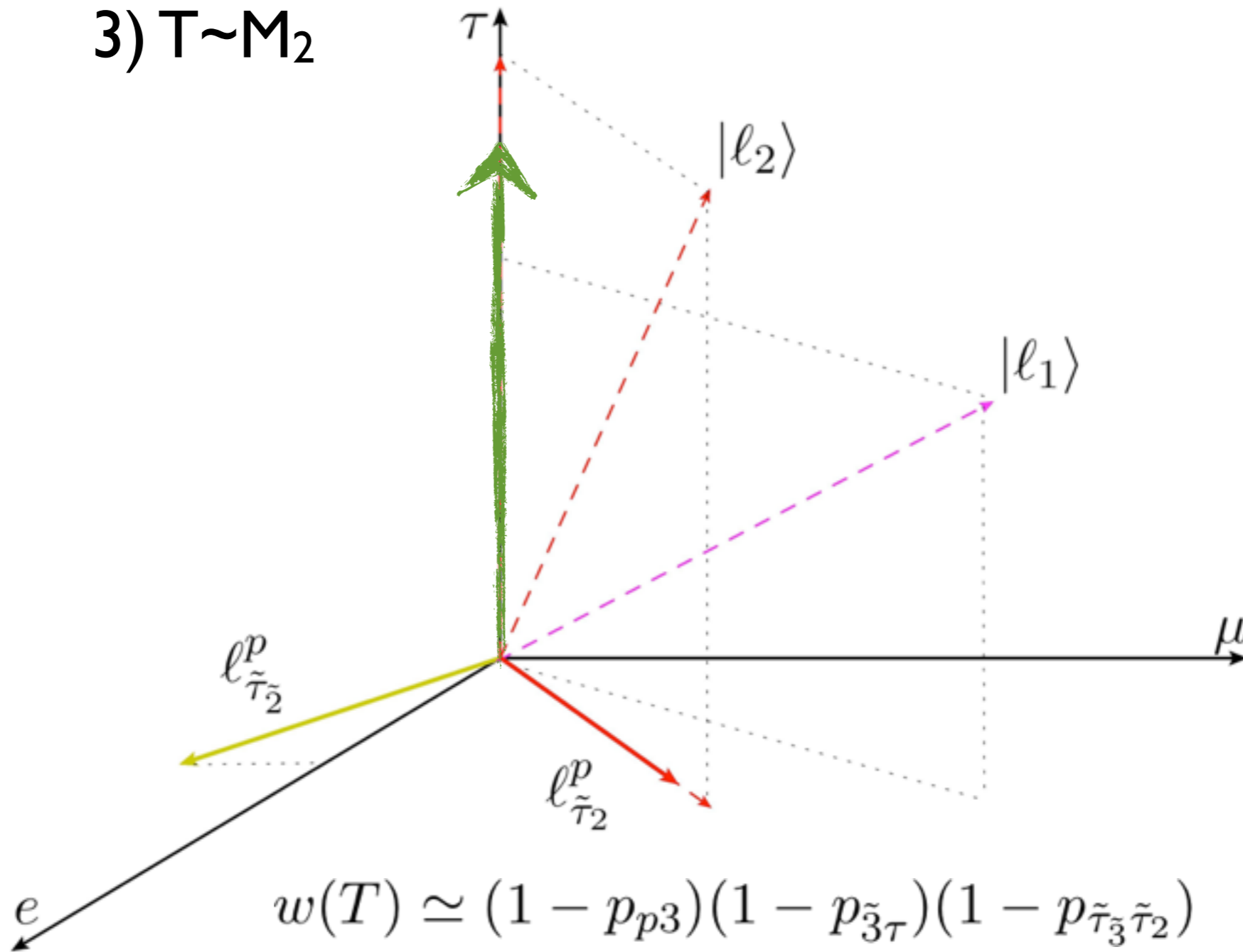
The τ - N_2 scenario step by step



τ -Yukawa interactions break the heavy flavour state's coherence. The asymmetry along τ is now a pure Leptogenesis product

The τ - N_2 scenario step by step

3) $T \sim M_2$



Washout by the other component. Residual preexisting leptons are confined on the e - μ plane

